UCRL-ID-132137-01

# Deep Borehole Instrumentation along San Francisco Bay Bridges - 2001

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**May 1, 2001**

U.S. Department of Energy

Lawrence Livermore National Laboratory

This work was performed under the auspices of the U. S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

# Deep Borehole Instrumentation along San Francisco Bay Bridges - 2001

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March 1, 2001

## Abstract

This is a progress report on the Bay Bridges downhole network. Between 2 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, and San Rafael bridges in San Francisco Bay, California. The instruments will provide multiple use data that is important to geotechnical, structural engineering, and seismological studies. The holes are between 100 and 1000 ft deep and were drilled by Caltrans. There are twenty-one sensor packages at fifteen sites. The downhole instrument package contains a three component HS-1 seismometer and three orthogonal Wilcox 731 accelerometers, and is capable of recording a micro g from local M =1.0 earthquakes to 0.5 g strong ground motion form large Bay Area earthquakes. This report list earthquakes and stations where recordings were obtained during the period February 29, 2000 to November 11, 2000. Also, preliminary results on noise analysis for up and down hole recordings at Yerba Buena Island is presented.

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## Introduction

This is a progress report on the Bay Bridges downhole network. The Bay Bridges down hole network consists of recordings in bore holes that are drilled 100 ft into bedrock along and in the San Francisco Bay (Figure 1). Between 1 and 8 instruments have been spaced along the Dumbarton, San Mateo, Bay, Carquinez, and San Rafael bridges. Tables 1 - 5 list recording site information, and Figure 1 shows instrument locations. In addition, two vertical arrays exist at the Dumbarton bridge with additional sensors at the surface and at 200 ft (Table 1). Two sensors are currently located at the surface at the Bay Bridge and are waiting drill holes. Prior to this study few seismic recording instruments existed in bedrock in San Francisco Bay. This left a recording gap for engineering studies of the Bay bridges and in seismicity studies of the Bay Area. The Bridges network is part of a larger Hayward Fault Digital Network, see Figure 1.

There are six primary areas of research by LLNL that will be enhanced by the bore hole instrumentation: 1) developing realistic predictions of strong ground motion at multiple input points along long span bridges, 2) examining ground motion variability in bedrock, 3) calibrating soil response models, 4) developing bridge response calculations with multiple support input motions, 5) evaluate the seismicity of potentially active faults in the San Francisco Bay, and 6) record strong ground motion.

Key to these studies is LLNL's effort to exploit the information available in weak ground motions (generally from earthquakes < M=3.0) to enhance predictions of seismic hazards. Although strong ground motion recordings are essential to calibrate models and understand the hazard of future earthquakes, we can obtain weak ground motion data immediately, whereas it may be years before strong motion data is recorded. Following is an expansion of research goals utilizing recordings from the Bridges Network.

*1)* *prediction of strong ground motion*: LLNL is developing a methodology of using weak ground motion to synthesize linear response strong ground motion and incorporating this with constraints on fault rupture scenarios to predict strong ground motion. These computations provide estimates of the full wavetrain ground motion at multiple points along long span structures.

*2)* *ground motion variability*: Recent studies have demonstrated the high variability of strong ground motion with site conditions. Recordings along Bay bridges will be used both to improve calculations of ground motions for bridges, and to research the spatial sensitivity and significance of site variability to structures.

*3)* *soils response*: LLNL is researching means of using weak ground motion to constrain soils models for non-linear computations. Current research has shown that low strain constitutive properties are significant to non-linear ground motion computations, and that these values can be significantly improved by an iterative process of matching weak motion solutions.

*4)* *bridge response calculations:* Current developments in structural dynamics allow non-linear, three-dimensional calculation of bridge response. This requires realistic full wavetrain input ground motions. LLNL is conducting research on the sensitivity of synthetic ground motions to accurate non-linear computations, and the significance of utilizing multiple support input calculations.

5) *seismicity:* Location of small earthquakes within the Bay that may indicate the existence of active faults will be made possible with the instrumentation. Very small earthquakes (M<2) cannot be recorded adequately to determine accurate locations by regional networks.

6) *strong ground motion:* Strong ground motion from previous earthquakes gives a good indication of what might be expected from future earthquakes. In addition recent earthquakes have demonstrated the high variability of strong ground motion so that an array of strong ground motion recordings will give a better understanding of the ground motion variability from future earthquakes.

## Instrumentation

As a result of collaboration between the Berkeley Seismographic Station Hayward Fault Network, Lawrence Livermore National Laboratory, and Caltrans, a seismic network of eight instruments was installed in boreholes (one surface recorder awaits a borehole) along the SFOBB (Hutchings et al, 1999). In addition, a temporary surface recorder was installed above the borehole on the east side of YBI near Pier E2 of the SFOBB. Tables 1-5 list the recording site locations for instruments at all bridges in this study. Table 6 lists instrument orientations, previously discussed in report for 1999. Figure 1 shows the location of the bridges.

The down-hole sensor package is manufactured at LBL under the direction to Dr. Tom McEvilly, and is the same package used by the USGS and LBL for the Hayward Fault Digital Recording Network. This package contains three orthogonal Oyo HS-1 4.5 Hz geophones and a three orthogonal Wilcoxon 731s 10v/g accelerometers. The dynamic range of the Wilcoxon package is from a micro-g to 0.5 g acceleration, and is flat to frequency response from 0.1 to 300 Hz. This allows recording of M =1.0 to 0.5 g strong ground motion form large Bay Area earthquakes. Typically, the Wilcoxon's are recorded over two dynamic ranges to capture weak and strong ground motions, and HS-1's are used as a backup for weak ground motion recording. Portable Refraction Technology 72A Data Acquisition Systems with 16 bit resolution and 200 Hz sampling are used to record the data at most sites. Three sites utilize Quantera-4120 24-bit resolution data loggers with 500 Hz recorders. The data is processed and managed at UC Berkeley. Tables 1-5 list site and instrumentation information for the recording sites.

Table 7 lists the events located at the Bay Bridge during this period. Table 8 lists the events recorded at each station.

## Preliminary Results

A temporary surface recorder was installed above the borehole on the east side of YBI. Figure 2 shows the location of the borehole on YBI (located at 37.8143 N, -122.3582 W). The uphole site is referred to as BE2U and the downhole site is referred to as BE2D. We identified 18 events that were recorded on both the top and bottom of the borehole (Table 9). Locations and magnitudes listed in Table 9 are from the Northern California Earthquake Data Center (UCB, 1999). The locations of the 18 events are plotted in Figure 2.

BE2U has a reftek recorder and a S-6000 seismometer, and BE2D has a Quanterra recorder and Wilcoxon 731s 10v/g accelerometers. BE2D also contains three orthogonal Oyo HS-1, 4.5 Hz geophones for backup. The dynamic range of the Wilcoxon package is from a micro-g to 0.5 g acceleration, and typically records nearby microearthquakes greater than about M =1.0 as well as strong ground motion. The S-6000 clips at accelerations near 0.002 g, so we are limited to recordings smaller or distant events at BE2U.

We have removed the response of each system to get ground motion to the frequency limit of the systems. The Wilcoxon accelerometers and Quanterra recorder (downhole system) are flat for acceleration from 0.1 Hz to the anti-alias filter at 100 Hz. The low frequency limit is from a high pass filter in the power box. It is down 3 db at 0.1 Hz and rolls off at 6 db per octave. The sensor has a roll-off at 0.05 Hz. The data was corrected for the 0.1 Hz high pass filter, so it is band limited by the sensor roll-off.

A portable Refraction Technology 72A Data Acquisition Systems with 16 bit resolution was used to record the S-6000 seismometer at BE2U. The reftek recorder has a roll-off at 250 Hz and imposes an anti-aliasing filter at 40% of the sampling rate. We sampled the reftek data at 200 sps, so it has a band limit of 80 Hz. The S-6000 seismometer is flat to velocity to at least 100 Hz and rolls off at the low frequency end; it is down 3 db at 2 Hz and rolls off at 12 db per octavo. We have corrected for this high pass filter, so that the response is effectively flat to DC.

Together, BE2D and BE2U have common data from 0.05 to 80 Hz. However, instrument and cultural noise further limit the effective frequency band of the data. Therefore the signal to noise ratios (SNR) were calculated and evaluated to determine the usable frequency band of the data recorded for each earthquake. This is reported below and usable frequency band are listed for each event in Table 1. The downhole ground motions were recorded as accelerations and were therefore integrated to velocities to be consistent with the uphole recordings.

### *Signal to Noise Ratios*

For weak motion recordings, the noise in the signal is often the limiting factor for site response studies. The SNR for each earthquake in this study was calculated by estimating the spectral content of the first 20 to 30 seconds of the record (depending on the length of noise recorded prior to the earthquake signal) and a similar length of the earthquake signal. The two components of horizontal motion were combined into a complex signal as described by Steidl et al (1996). Fourier amplitude spectra of velocity records are used for the analysis. The Fourier signal amplitude spectrum was then divided by the Fourier noise spectrum for that earthquake. The SNR was calculated for the uphole and downhole recorded motions. A limiting SNR of 3:1 was chosen to determine the usable frequency band of each signal. Frequencies where the SNR was below 3 are believed to be contaminated by the noise. The usable frequency bands for the uphole and downhole ground motions for each earthquake in this study are listed in Table 9.

Figure 3-20 show signal and noise for all the events. Examination of the noise and signal spectra for all 18 events in this study results in the following conclusions. The SNR for the uphole recordings was generally greater than 3 over a frequency range of 0.5 to 30 Hz. The downhole recordings had a much smaller usable frequency range with SNR equal to or above 3, from 1 to 8 Hz. However, the usable frequency range varies over the recorded earthquakes. The earthquakes with magnitudes greater than or equal to 3.0 tended to have a wider frequency band of high SNR.

One of the potential advantages to downhole instruments is the reduced cultural noise. Unfortunately for most of the recorded events in this study, instrument noise is more of a controlling factor. Because the YBI uphole and downhole instruments are different, the usable frequency band is also different for each instrument. The downhole Wilcoxon 731s 10v/g accelerometer can be limited by noise at low frequencies, generally below 1 Hz, except for the larger events in the study where the SNR is greater than 3 down to 0.3 Hz. On the other hand, the uphole S-6000 seismometer is less limited at the low frequencies down to 0.2 Hz in some cases but can be limited at high frequencies for small amplitude events. In particular, the S-6000 has a significant increase in noise for frequencies above 30 Hz. The Wilcoxon instrument has less instrument noise at the higher frequencies and therefore results in a higher SNR above 10 Hz than the downhole instrument. So unfortunately for this uphole/downhole pair, the uphole instrument is limited by noise for high frequencies and the downhole instrument is limited at low frequencies when recording weak motion. Both instruments have high SNR for the larger earthquakes.

## References: LLNL related research papers

Baise, Laurie, Lawrence Hutchings, and Steven Glaser (2001) Analysis of Site Response at Yerba Buena Island, San Francisco Bay, California from Weak Motion Recordings. in press, Special Issue on Site Response, Bollettino di Geofisica, Trieste, Italy.

Hutchings, L. (1991). "Prediction" of strong ground motion for the 1989 Loma Prieta earthquake using empirical Green's functions, Bull. Seis. Soc. Am. 81, 88-121.

Hutchings, L. and F. Wu (1990). Empirical Green's functions from small earthquakes: A waveform study of locally recorded aftershocks of the San Fernando earthquake, J. Geophys. Res. 95, 1187-1214.

Hutchings, L., P. Kasameyer, W. Foxall, J. Hollfelder, C. Turpin, C. Hayek, R. Uhrhammer, S. Jarpe (1999) Deep Borehole Instrumentation Along San Francisco Bay Bridges - 1999. Lawrence Livermore National Laboratory, UCRL 132137.

Hutchings, L., P. Kasameyer, C. Turpin, L. Long, W. Foxall, J. Hollfelder, T. McEvilly, R. Clymer, and R. Uhrhammer (2000) Deep Borehole Instrumentation Along San Francisco Bay Bridges - 2000. Lawrence Livermore National Laboratory, UCRL 132137-00.

Hutchings, Lawrence (1999) Strong Ground Motion Estimates for the University of California, Santa Barbara Campus from a M=6.8 Earthquake on the North Channel-Pitas Point Fault. Lawrence Livermore National Laboratory, UCRL-ID-183645, pp 54.

Hutchings, Lawrence, Paul Kasameyer, William Foxall, Jennifer Hollfelder, Christine Turpin and Steven Jarpe (1999) Deep Bore Hole Instrumentation along the San Francisco Bay Bridges -

1996-1998. Lawrence Livermore National Laboratory UCRL-ID-132137, pp 28.

Hutchings, Lawrence, William Foxall, Stephen Jarpe, and Paul Kasameyer (1999) "Synthetic Strong Ground Motion at the Oakland/San Francisco Bay Bridges from an M=8.0 Earthquake on the San Andreas Fault and a M=7.25 Earthquake on the Hayward Fault",Lawrence Livermore National Laboratory, UCRL-ID-183645, pp 64.

Hutchings, Lawrence, Steven Jarpe, Paul Kasameyer (1998) Validation of a Ground Motion Synthesis and Prediction Methodology for the 1988, M=6.0, Saguenay Earthquake. Lawrence Livermore National Laboratory, UCRL-JC-129395, pp. 36.

Hutchings, L. (1988). Modeling strong earthquake ground motion with an earthquake simulation program EMPSYN that utilizes empirical Green's functions, Lawrence Livermore National Laboratory, Livermore, CA, *UCRL-ID-105890*, p. 122.

Hutchings, L. (1991). "Prediction" of strong ground motion for the 1989 Loma Prieta earthquake using empirical Green's functions, *Bul. Seis. Soc. Am.* **81**, 88–121.

Hutchings, L. (1994) Kinematic Earthquake Models and Synthesized Ground Motion Using Empirical Green's Functions. *Bul. Seis. Soc. Am.* **84**, pp. 1028-1050.

Hutchings, L.J., P. Goldstein, S.P. Jarpe, and P.W. Kasameyer (1992) Prediction of Broadband Near-field Strong Earthquake Ground Motion along an Extended Structure from an Extended Fault Rupture. Seis Res Let, {**63**},(1), January - March 1992.

Hutchings, L., E. Ioannidou, S.P. Jarpe, G.N. Stavrakakis, and P. Kasameyer. Strong Ground Motion Synthesis for a M=7.2 earthquake in the Gulf of Corinth, Greece using Empirical Green's functions, presented, 29th IASPEI General Assembly, Thessaloniki, Greece, August 18-28,1997

Hutchings, L. and S. Jarpe (1995) Ground motion Variability at the Highways 14 and I-5 Interchange in the Northern San Fernando Valley. *Bul Seis Soc Am.* **84**, pp. 1028-1050.

Hutchings, L. and F. Wu (1990). Empirical Green's functions from small earthquakes—A waveform study of locally recorded aftershocks of the San Fernando earthquake, *J. Geophys. Res.* **95**, 1187–1214.

Jarpe, S.P., L.J. Hutchings, T.F. Hauk, and A.F. Shakel (1989) Selected Strong- and Weak-Motion Data from the Loma Prieta Earthquake Sequence. {Seis Res Letters},{**60**}, 167-176.

Jarpe, S.P. and Kasameyer, P.K. (1994) Validation of a Methodology for Predicting Broadband-Strong Ground Motion Time Histories from Empirical Green's Functions. Jarpe, S.P. and P.W. Kasameyer (1995). Validation of a Methodology for Predicting Broadband Strong Motion Time Histories from Empirical Green's Functions. in press, *Bul. Seis. Soc. Am.*

Mualchin, Lalliana, Pat Hipley, Lawrence Hutchings, Jennifer Hollfelder, Steve Jarpe, and Kazuoh Seo (1998) Wave Propagation along the San Francisco, California Bay Bridge. proceedings, *Second International Synposium on the Effects of Surface Geology on Seismic Motion*, Yokohama, Japan, December 1-3, pp 22-31.

Steidl, Jamison H., Alexei G. Tumarkin, and Ralph J. Archuleta (1996) What is a reference site? Bul. Seis. Soc. Am. 86, pp. 1733-1748.

## Acknowledgments

This work was funded by Caltrans, contract no. 59A0238. Instrumentation was been made possible by the personnel support of, Caltrans, Sacramento, California, in particular: Pat Hipley, Lalliana Mualchin, Reid Buell, John Bowman, Mark Palmer, Kathy Amaru, James Dent, and Robert Fletcher. Extensive instrument financial support was contributed by UCB, LBL, LLNL-LDRD, U.C. Campus/Laboratory Collaboration (CLC) program, and USGS. This would not have been possible without the generous contribution of temporary recording instrument provided by the LLNL Seismic Observatory and LBL Instrumentation Program.

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**Table 1: Dumbarton Bridge Recording sites**

| i.d. | sensors | latitude | longitude | depth (m) | sensor h1, h2 + 090 | Recording |
|---|---|---|---|---|---|---|
| Pier 01 | | 37.49947 | 122.12755 | | | |
| DWA, | S-13 | | | 00.0 m, abut. | N320°E | 07/94 - 09/94 |
| DWS | Wil-731-200, HS-1 | | | 01.5, Pier 01 | 000° | 09/94 - 09/94 |
| DWN | Wil-731-200, HS-1 | | | 71.6, " | --- | 09/94 - 09/94 |
| DWB | HS-1, HS-1 | | | 228.0, " | 033° | 08/93 - present |
| Pier 27 | | | | | | |
| DMB | Wil-731,HS-1 | 37.50687 | 122.11566 | 189.2, Pier 27 | N020°E | 07/94 - present |
| CAP | Wil-731-200, HS-1 | 37.517 | 122.104 | pile cap, Pier 27 | | 07/92 - 11/92 |
| Pier 44 | | 37.51295 | 122.10857 | | | |
| DES | Wil-731-200, HS-1 | | | 01.5, Pier 44 | N000°E | 11/94 - 09/94 |
| DEM | Wil-731-200,HS-1 | | | 62.5 | ---- | 09/94 - 09/94 |
| DEB | Wil-731, HS-1 | | | 157.9 | 097° | 07/94 - present |

**Table 2: Bay Bridge Recording sites**

| i.d. | sensors | latitude | longitude | depth (m) | sensor h1, h2 + 090 | Recording |
|---|---|---|---|---|---|---|
| SFA | S-6000 | 37.7861 | 122.3893 | 00.0 m, | N143°E | 6/98-present |
| BBW2 | Wil-731A,HS-1 | 37.79120 | 122.38525 | 57.6 | N042°E | 4/96-present |
| BBW5 | Wil-731A,HS-1 | 37.8010 | 122.3737 | 36.3 | N142°E | 1/97-present |
| YBA | Wil-731A,HS-1 | 37.8094 | 122.3645 | 3.0 | N150°E | 6/98-present |
| BE2U | S-6000 | 37.81427 | 122.35815 | 0.00 | N220°E | 7/96-present |
| BE2D (YBIB) | Wil-731A,HS-1 | 37.81427 | 122.35815 | 60.96 | N165°E | 7/96-present |
| BE07 | Wil-731A,HS-1 | 37.81847 | 122.34688 | 134.0 | N117°E | 2/96-present |
| BE17 | Wil-731A,HS-1 | 37.82086 | 122.33534 | 160.0 | N168°E | 8/95-present |
| BE23 | HS-1 | 37.82167 | 122.32867 | 150 | N---°E | 3/94-10/95 |

**Table 3: San Rafael Bridge Recording sites**

| i.d. | sensors | latitude | longitude | depth | sensor h1, h2 + 090 | Recording |
|---|---|---|---|---|---|---|
| P34 | Wil-731A,HS-1 | 37.93583 | 122.44540 | 109.0 m | | 8/97-present |
| P58 | Wil-731A,HS-1 | 37.93372 | 122.41313 | 44.0 m | N0°E | 6/97-present |

**Table 4: San Mateo Bridge Recording sites**

| i.d. | sensors | latitude | longitude | depth | sensor h1, h2 + 090 | Recording |
|---|---|---|---|---|---|---|
| P343 | Wil-731A,HS-1 | 37.59403 | 122.23242 | 298.0 m | N0°E | not recorded |

**Table 5: Carquinez Bridge Recording sites**

| i.d. | sensors | latitude | longitude | depth | sensor h1, h2 + 090 | Recording |
|---|---|---|---|---|---|---|
| CRQB | Wil-731A,HS-1 | 38.05591 | 122.22402 | ------- | N0°E | 6/98-present |

**Table 6: Sensor Orientation Calculations, Bay Bridge**

| Orientations of up on channel 2; ch3 = ch2 + 090; Channel 1 is vertical, positive down, except ** | SFA** | BBW2 | BBW5 | YBA** | BE2D | BE2U | BE07 | BE17 | BE23 |
|---|---|---|---|---|---|---|---|---|---|
| 9812041216 | N143E | N042E | N142E | N150E | N165E | N310E | N117E | N168E | |
| +prior 08/24/99<br>since 08/24/99<br><br>*prior 01/15/97<br>since 01/15/97 | N131E<br>N136E | | | | | N143E<br>N310E | | | |
| | | | | | | | | | |
| **Vertical** | | | | | | | | | |
| vertical: up on channel-1 | UU | DD | DD | DD | DD | UU | DD | DD | |

**Table 7: Events recorded by Bay Bridge Network**

| Earthquake | Time | Latitude | Longitude | Depth | Mag | Fault |
|---|---|---|---|---|---|---|
| 2000/02/29 | 10:48:00.58 | 37.7980 | -121.9428 | 15.94 | 2.05 | Calaveras |
| 2000/02/29 | 11:10:09.72 | 37.8682 | -122.2392 | 10.52 | 2.15 | Hayward |
| 2000/03/02 | 09:22:12.21 | 37.2578 | -121.6400 | 6.01 | 1.45 | Calaveras |
| 2000/03/28 | 21:03:07.27 | 37.6330 | -122.0203 | 6.04 | 3.04 | San Andreas |
| 2000/04/03 | 06:08:35.89 | 37.4342 | -121.7775 | 9.00 | 1.56 | Calaveras |
| 2000/04/06 | 19:03:06.54 | 38.3492 | -122.1980 | 8.04 | 2.61 | Hayward |
| 2000/04/09 | 21:25:22.16 | 38.0880 | -122.4033 | 13.31 | 2.40 | San Andreas |
| 2000/04/10 | 13:05:29.64 | 37.4747 | -121.7150 | 9.70 | 3.20 | Calaveras |
| 2000/04/11 | 14:12:15.93 | 37.8447 | -122.0097 | 14.87 | 2.52 | Calaveras |
| 2000/04/14 | 12:22:31.77 | 37.9830 | -122.0433 | 15.76 | 3.19 | Calaveras |
| 2000/04/14 | 17:49:25.62 | 37.6038 | -121.9708 | 9.89 | 3.04 | Calaveras |
| 2000/04/24 | 08:03:51.47 | 37.4018 | -121.7267 | 5.45 | 1.24 | Calaveras |
| 2000/04/29 | 06:04:49.01 | 37.7378 | -122.5512 | 7.22 | 2.51 | San Andreas |
| 2000/05/02 | 10:14:45.67 | 37.9222 | -122.2905 | 6.54 | 2.19 | San Andreas |
| 2000/05/03 | 22:05:11.80 | 37.7277 | -122.1177 | 8.46 | 2.28 | Hayward |
| 2000/05/14 | 14:11:49.05 | 37.3338 | -122.0613 | 4.06 | 2.39 | Hayward |
| 2000/05/21 | 05:07:02.82 | 37.7737 | -122.5888 | 6.62 | 2.13 | San Andreas |
| 2000/05/23 | 12:35:06.85 | 37.7113 | -122.1062 | 6.04 | 2.60 | Hayward |
| 2000/05/25 | 06:43:08.73 | 37.8652 | -122.2380 | 9.59 | 1.88 | Hayward |
| 2000/05/26 | 06:21:15.74 | 37.9898 | -122.1818 | 9.10 | 2.17 | Hayward |
| 2000/05/26 | 14:23:20.40 | 37.9517 | -122.7218 | 7.67 | 2.28 | San Andreas |
| 2000/05/28 | 04:30:06.37 | 37.5677 | -122.4317 | 10.11 | 1.21 | San Andreas |
| 2000/05/30 | 02:10:58.51 | 37.3072 | -122.0778 | 4.97 | 2.58 | Hayward |
| 2000/05/30 | 08:10:41.59 | 37.3482 | -121.7230 | 9.82 | 1.25 | Hayward |
| 2000/06/02 | 10:17:24.38 | 37.7512 | -122.1512 | 5.71 | 2.65 | Hayward |
| 2000/06/08 | 05:53:27.89 | 37.2958 | -121.6752 | 5.11 | 2.20 | Hayward |

| Earthquake | Time | Latitude | Longitude | Depth | Mag | Fault |
|---|---|---|---|---|---|---|
| 2000/06/13 | 11:48:11.55 | 37.3105 | -121.6805 | 7.51 | 3.47 | Hayward |
| 2000/06/17 | 00:52:09.94 | 37.7203 | -122.5725 | 3.28 | 2.02 | San Andreas |
| 2000/06/18 | 11:13:26.28 | 37.7652 | -121.9290 | 14.25 | 0.81 | Calaveras |
| 2000/06/18 | 17:16:07.64 | 37.9095 | -122.2938 | 3.42 | 1.33 | Hayward |
| 2000/06/25 | 07:23:18.26 | 37.1240 | -121.5265 | 7.83 | 3.63 | Calaveras |
| 2000/06/25 | 16:03:21.39 | 37.7318 | -122.5395 | 5.96 | 1.14 | San Andreas |
| 2000/06/25 | 16:04:35.30 | 37.7337 | -122.5397 | 5.75 | 1.56 | San Andreas |
| 2000/07/03 | 22:13:18.06 | 37.3420 | -121.7055 | 8.55 | 3.33 | Hayward |
| 2000/07/04 | 10:08:13.43 | 37.8030 | -122.0227 | 8.82 | 1.75 | Hayward |
| 2000/07/07 | 12:08:22.35 | 37.7160 | -122.5442 | 10.33 | 1.58 | San Andreas |
| 2000/07/09 | 14:43:47.46 | 37.8035 | -122.1823 | 8.38 | 1.77 | Hayward |
| 2000/07/11 | 23:40:20.68 | 37.1282 | -121.5302 | 7.46 | 2.32 | Hayward |
| 2000/07/14 | 11:23:16.39 | 38.0688 | -122.2405 | 7.63 | 1.97 | Hayward |
| 2000/07/15 | 07:29:20.47 | 37.8893 | -122.2603 | 4.72 | 1.07 | Hayward |
| 2000/07/15 | 11:56:38.97 | 37.9752 | -122.0335 | 15.43 | 3.61 | Hayward |
| 2000/07/18 | 02:02:01.45 | 37.6095 | -122.4752 | 8.33 | 1.83 | San Andreas |
| 2000/07/31 | 03:01:07.83 | 37.4185 | -121.7667 | 7.76 | 2.25 | Calaveras |
| 2000/08/22 | 10:00:57.97 | 38.4065 | -122.1558 | 3.64 | 0.62 | Hayward |
| 2000/09/02 | 08:00:30.44 | 37.9887 | -122.0557 | 15.63 | 2.35 | Calaveras |
| 2000/09/02 | 21:58:47.87 | 37.9877 | -122.0538 | 16.23 | 2.51 | Calaveras |
| 2000/09/03 | 08:36:30.09 | 38.3788 | -122.4127 | 10.21 | 5.17 | Hayward |
| 2000/09/03 | 09:11:15.97 | 38.3922 | -122.4032 | 6.10 | 1.64 | Hayward |
| 2000/09/03 | 21:00:03.07 | 38.3648 | -122.3998 | 8.58 | 2.31 | Hayward |
| 2000/09/09 | 03:02:16.36 | 37.6513 | -122.0443 | 5.23 | 2.03 | Hayward |
| 2000/09/10 | 12:37:19.34 | 38.3817 | -122.4088 | 7.13 | 2.55 | Hayward |
| 2000/09/12 | 06:55:26.17 | 37.5533 | -121.6765 | 5.18 | 2.49 | Calaveras |
| 2000/09/18 | 22:31:47.99 | 37.9173 | -122.3017 | 1.56 | 1.08 | Hayward |

| Earthquake | Time | Latitude | Longitude | Depth | Mag | Fault |
|---|---|---|---|---|---|---|
| 2000/09/23 | 23:16:52.87 | 37.8937 | -122.2188 | 7.55 | 2.14 | Hayward |
| 2000/09/24 | 22:27:46.52 | 37.8773 | -122.2313 | 10.02 | 1.53 | Hayward |
| 2000/09/27 | 10:18:55.23 | 37.8500 | -122.2325 | 6.07 | 2.26 | Hayward |
| 2000/09/28 | 08:44:06.49 | 37.3593 | -121.7262 | 6.96 | 2.48 | Hayward |
| 2000/10/03 | 11:30:54.65 | 37.6400 | -122.4945 | 8.09 | 1.99 | San Andreas |
| 2000/10/27 | 05:47:56.59 | 37.7603 | -122.1677 | 6.01 | 2.28 | Hayward |
| 2000/10/30 | 20:33:56.72 | 37.6695 | -122.4938 | 11.80 | 2.06 | San Andreas |
| 2000/11/12 | 17:49:56.34 | 37.9705 | -122.3407 | 6.89 | 2.55 | Hayward |

**Table 8: Events recorded at each station.**

| Earthquake | BBW2 | BBW5 | BE07 | BE17 | BE23 | SFA | YBA |
|---|---|---|---|---|---|---|---|
| 0002291048 | | | | | X | | |
| 0002291110 | | | X | | X | | |
| 0003020922 | | | | | | X | |
| 0003282103 | X | X | | | X | | |
| 0004030608 | | | | | | X | |
| 0004061903 | | | | | | | X |
| 0004092125 | | | | | X | | |
| 0004101305 | | | | | X | | |
| 0004111412 | | | X | | X | | |
| 0004141222 | | X | X | X | X | | |
| 0004141749 | X | X | X | X | X | | |
| 0004240803 | | | | | | X | |
| 0004290604 | X | | X | X | X | | |
| 0005021014 | X | | X | X | X | X | |
| 0005032205 | | | | | X | | |
| 0005141411 | | | | | X | | |
| 0005210507 | | | | | X | | |
| 0005231235 | X | | X | X | X | | |
| 0005250643 | | | X | X | X | | |
| 0005260621 | | | X | | X | | |
| 0005261423 | | | | | X | | |
| 0005280430 | | | | | X | | |
| 0005300210 | | | | | X | | |
| 0005300810 | | | | | | X | |
| 0006021017 | X | | X | X | X | | |
| 0006080553 | | | | | X | | |

| Earthquake | BBW2 | BBW5 | BE07 | BE17 | BE23 | SFA | YBA |
|---|---|---|---|---|---|---|---|
| 0006131148 | X | | | | X | | |
| 0006170052 | | | | | X | | |
| 0006181113 | | | | | | X | |
| 0006181716 | | | | | X | | |
| 0006250723 | X | | | X | X | | |
| 0006251604 | | | | | X | | |
| 0007032213 | | | | | X | | |
| 0007041008 | | | | | X | | |
| 0007071208 | | | | | X | | |
| 0007091443 | | | | | X | | |
| 0007112340 | | | | | X | | |
| 0007141123 | | | | | X | | |
| 0007150729 | | | | | X | | |
| 0007151156 | X | | | X | X | | |
| 0007180202 | | | | | X | | |
| 0007310301 | | | | | X | | |
| 0008221000 | | | | | | X | |
| 0009020800 | | | | X | | | |
| 0009022158 | | | | X | | | |
| 0009030836 | X | | | X | | X | |
| 0009030911 | X | | | | | | |
| 0009032100 | X | | | | | | |
| 0009090302 | | | | | X | | |
| 0009101237 | | | | | X | | |
| 0009120655 | | | | | X | | |
| 0009182231 | | | | | X | | |
| 0009232316 | | | | X | X | | |

| Earthquake | BBW2 | BBW5 | BE07 | BE17 | BE23 | SFA | YBA |
|---|---|---|---|---|---|---|---|
| 0009242227 | | | | | X | | |
| 0009271018 | | | | X | X | | |
| 0009280844 | | | | | X | | |
| 0010031130 | | | | | X | | |
| 0010270547 | | | | X | | | |
| 0010302033 | | | | X | | | |
| 0011121749 | | | | X | | | |

# San Francisco Bay Bridges

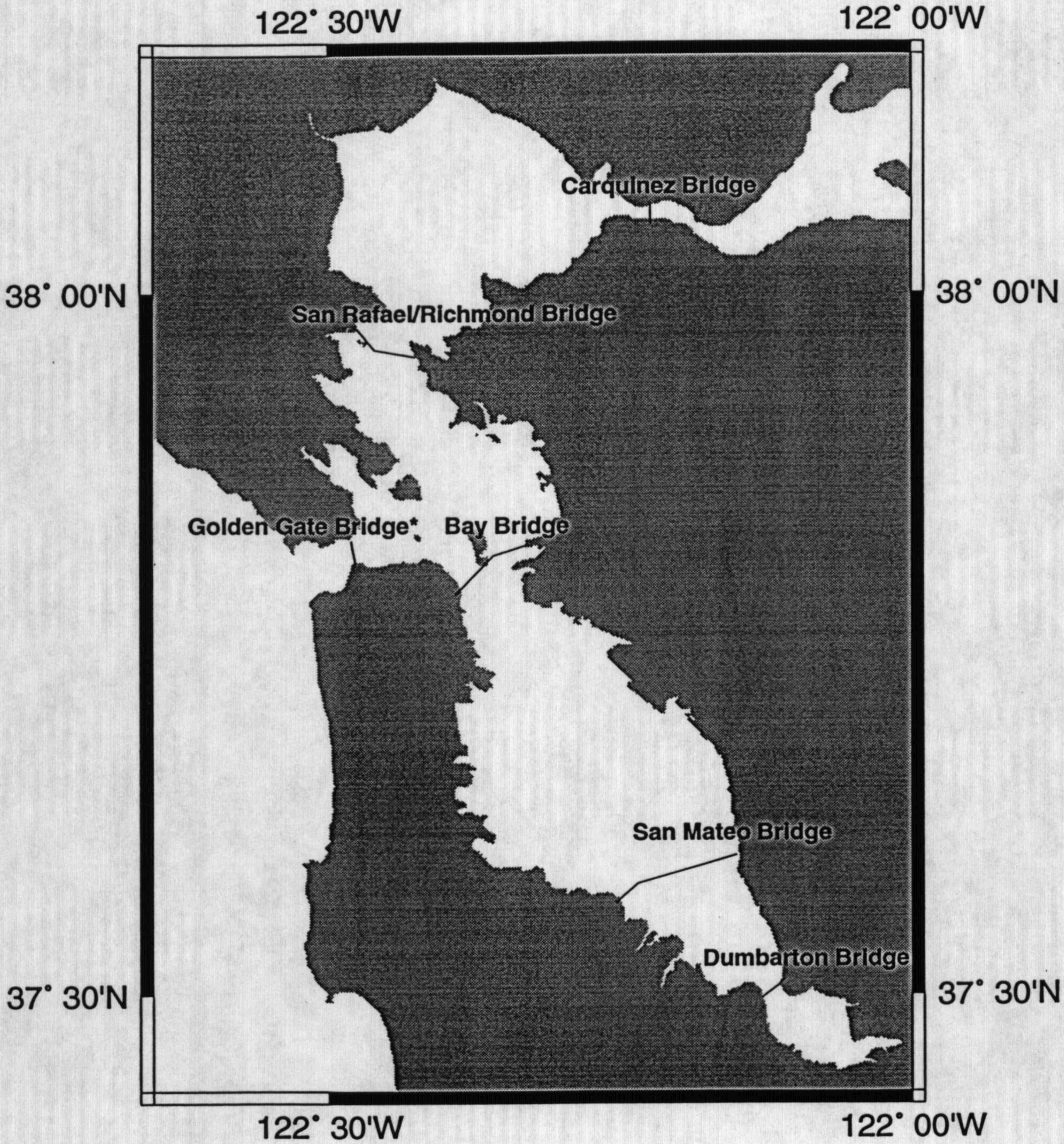
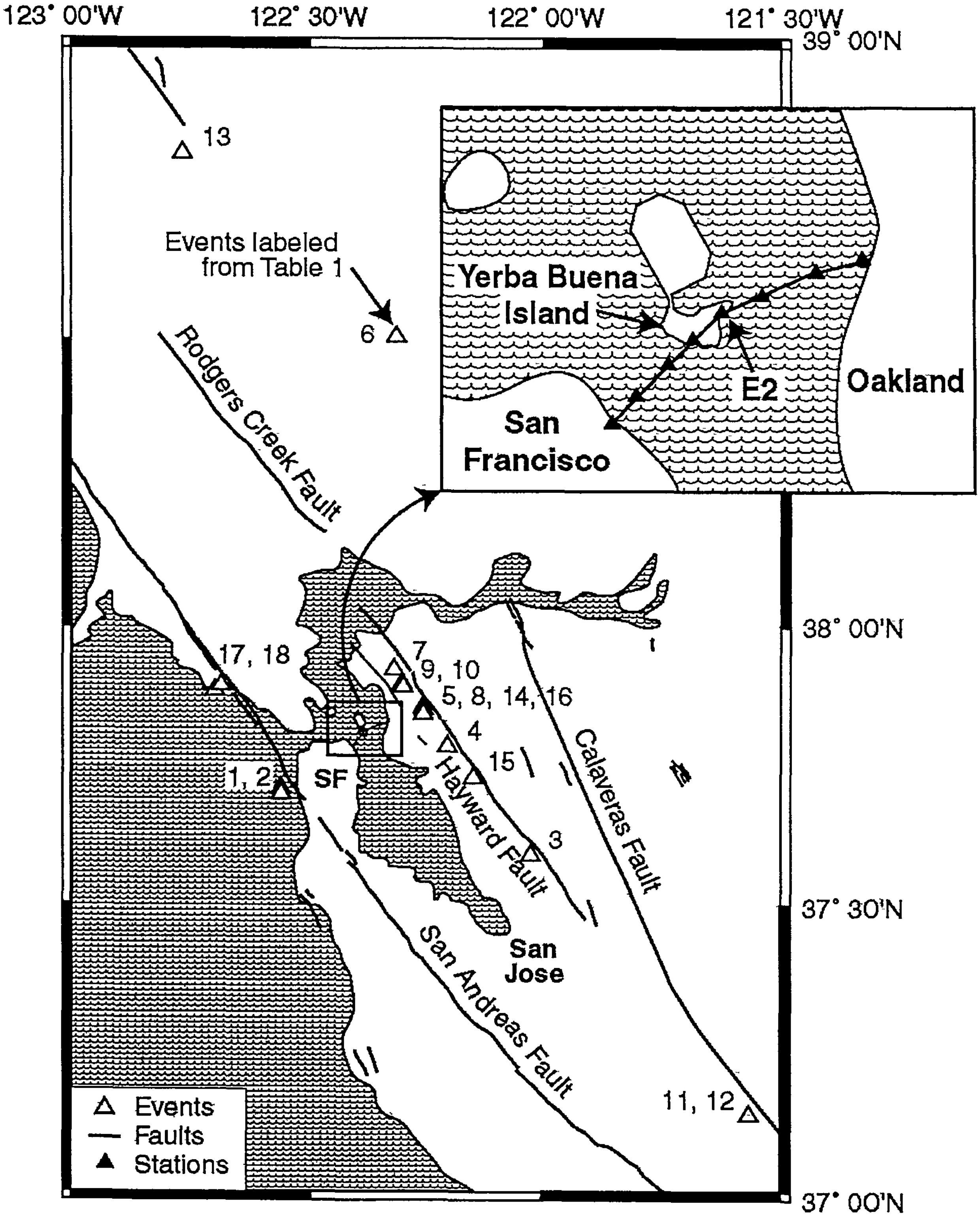
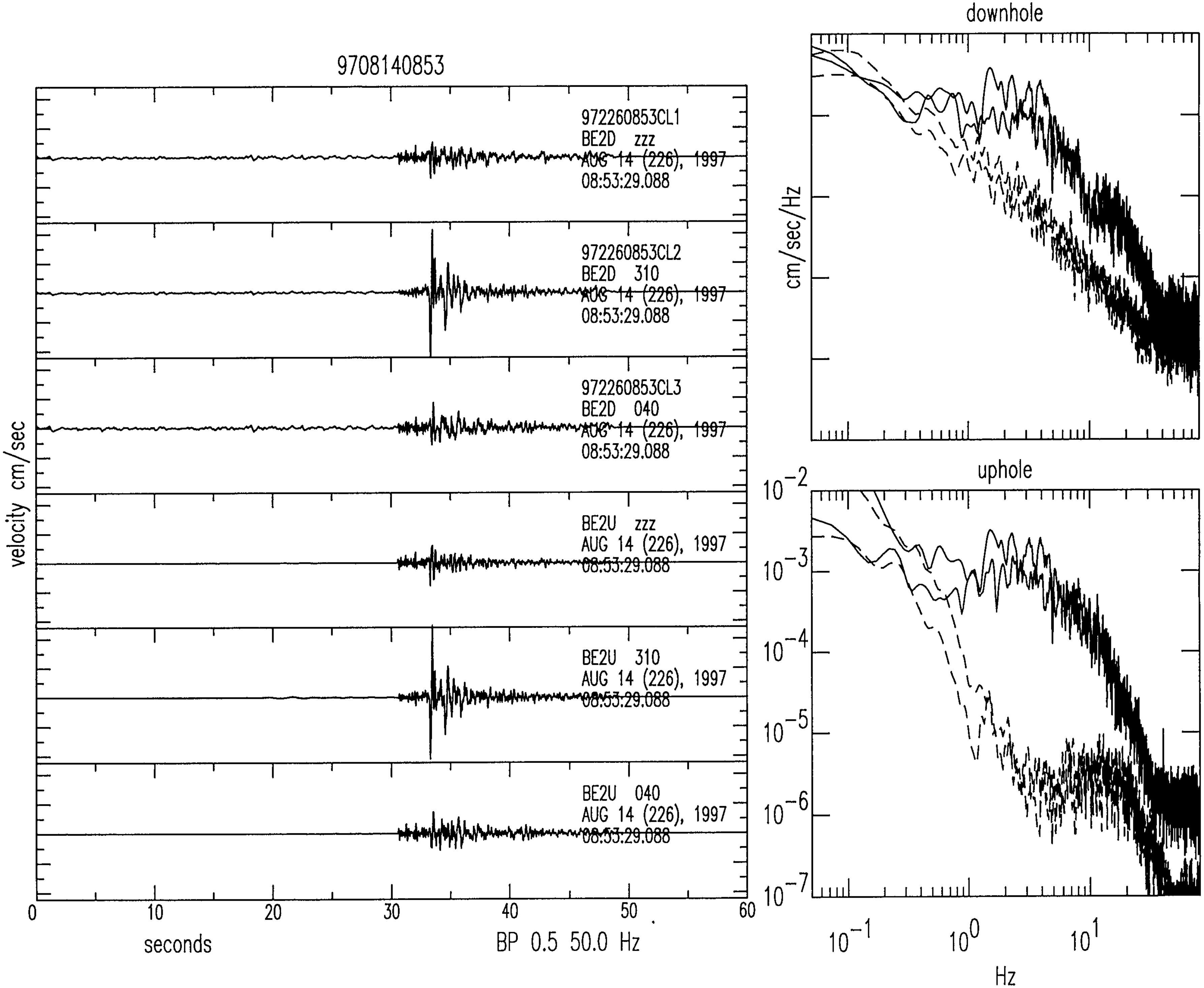



**Figure 1:** Map of the San Francisco Bay. (*Bridge not used in the bridge network study.)

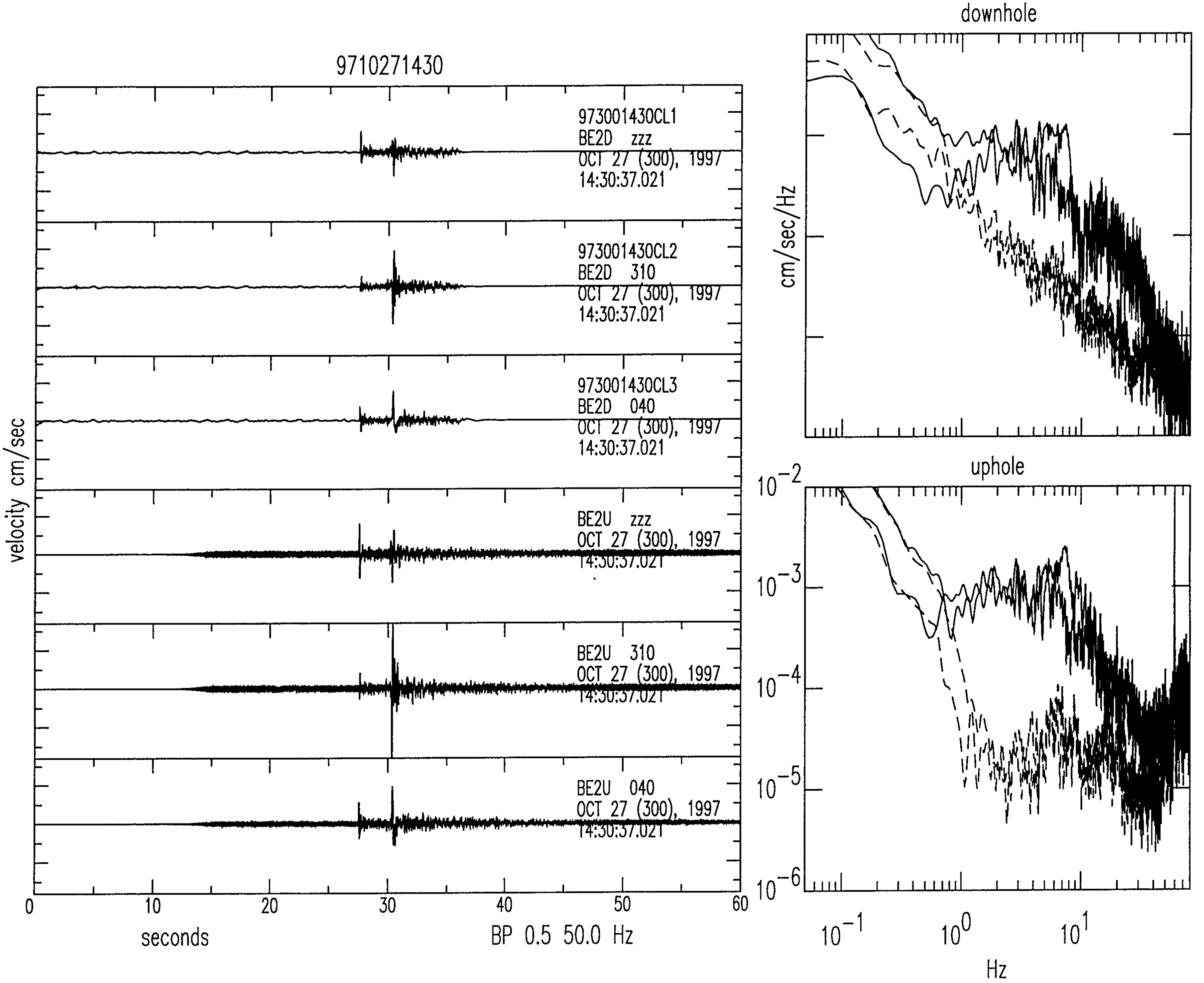


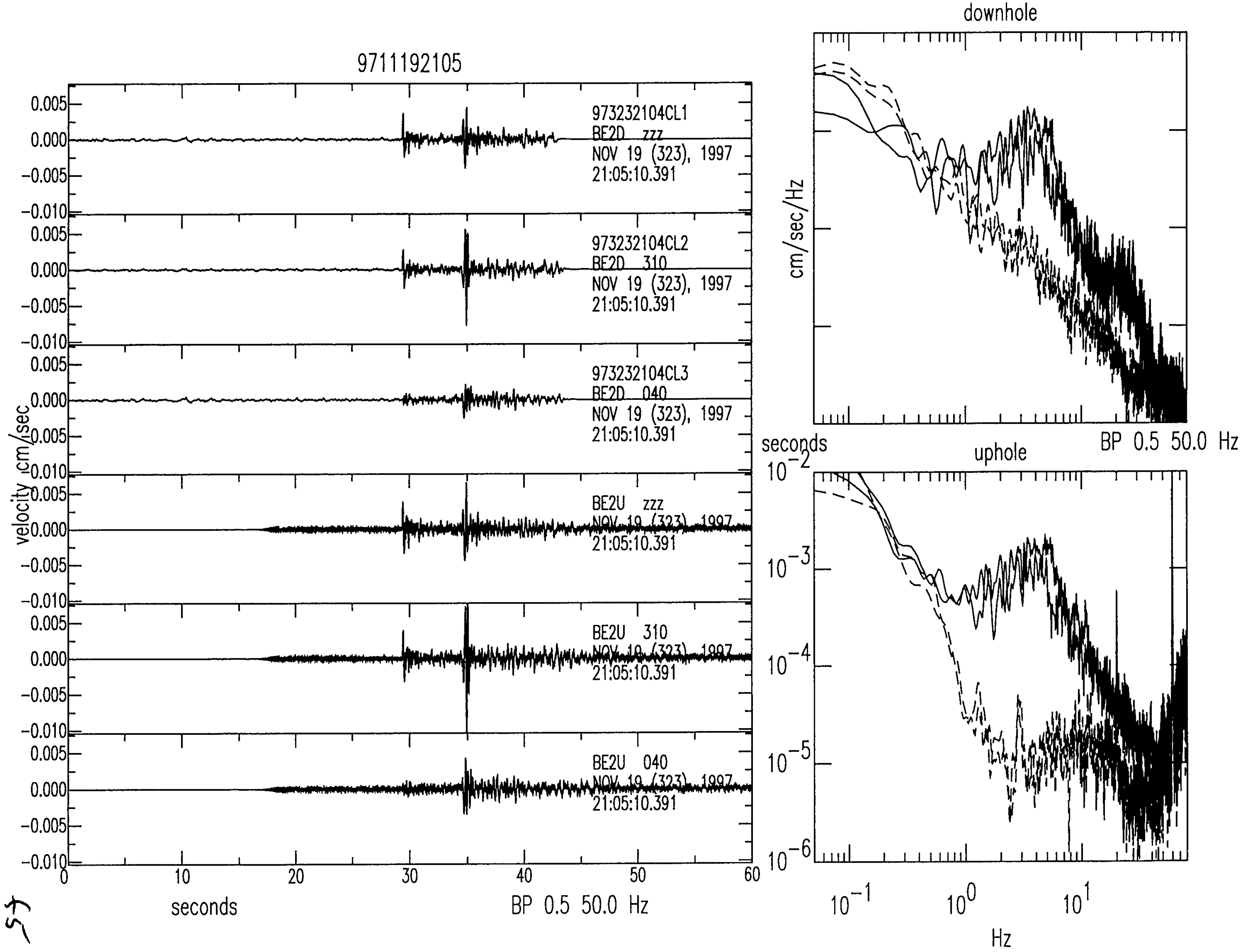
123° 00'W
122° 30'W
122° 00'W
121° 30'W
39° 00'N
38° 00'N
37° 30'N
37° 00'N
13
Events labeled from Table 1
6
Rodgers Creek Fault
Yerba Buena Island
E2
Oakland
San Francisco
17, 18
7
9, 10
5, 8, 14, 16
4
15
1, 2
SF
Hayward Fault
Calaveras Fault
3
San Jose
San Andreas Fault
11, 12
Events
Faults
Stations

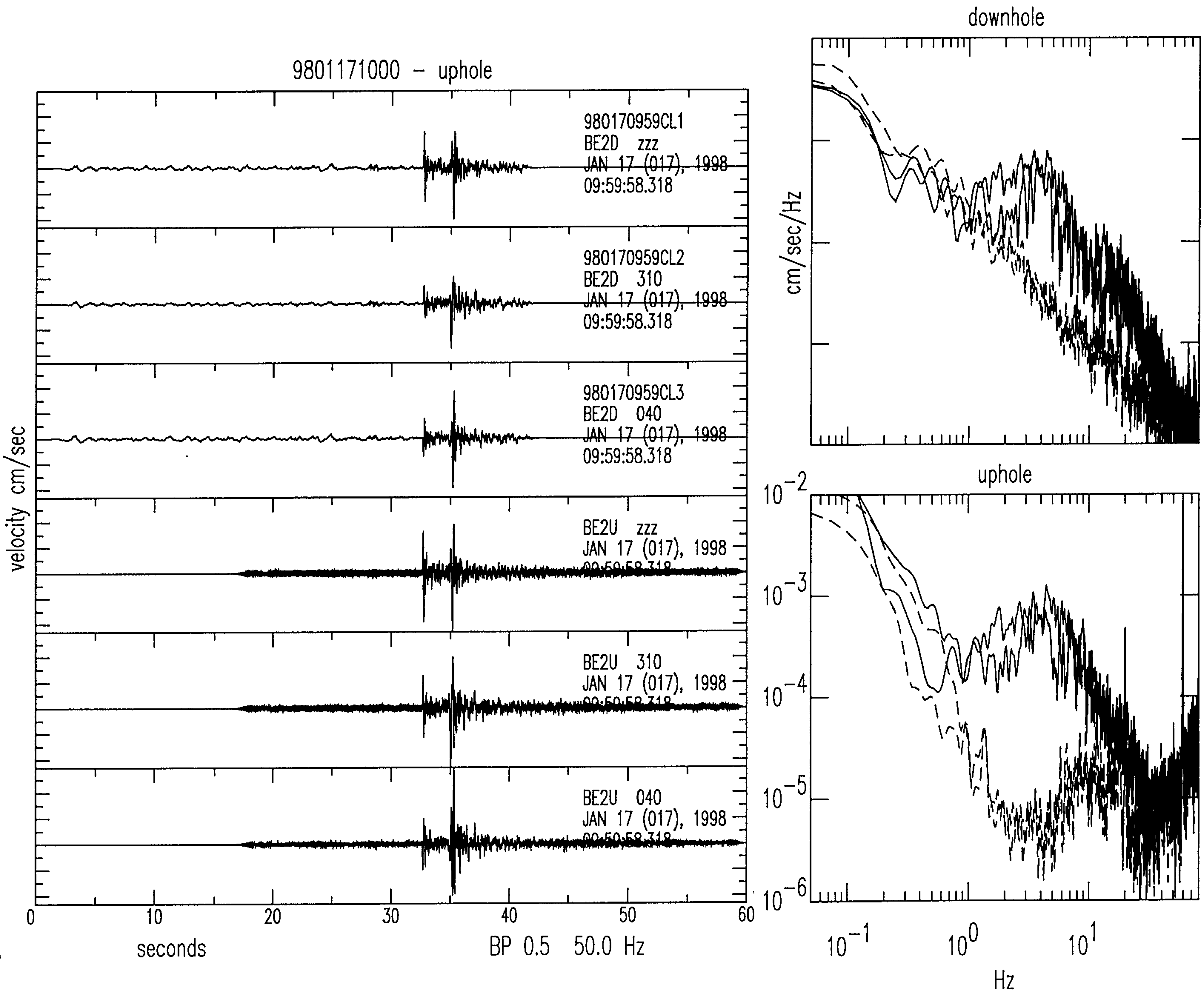


9708140853
972260853CL1
BE2D zzz
AUG 14 (226), 1997
08:53:29.088
972260853CL2
BE2D 310
AUG 14 (226), 1997
08:53:29.088
972260853CL3
BE2D 040
AUG 14 (226), 1997
08:53:29.088
BE2U zzz
AUG 14 (226), 1997
08:53:29.088
BE2U 310
AUG 14 (226), 1997
08:53:29.088
BE2U 040
AUG 14 (226), 1997
08:53:29.088
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
cm/sec/Hz
uphole
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

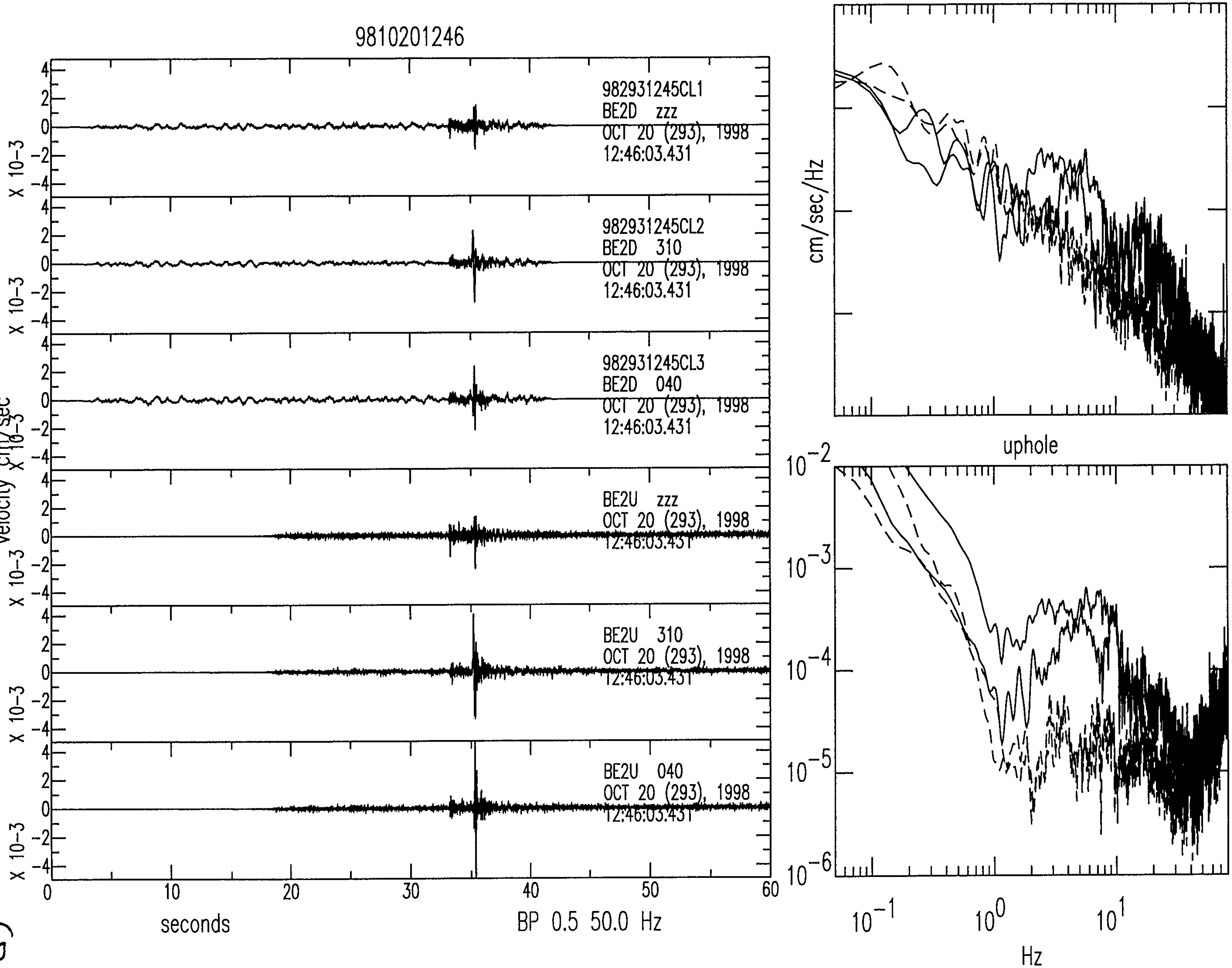
f3


9710271430
973001430CL1
BE2D zzz
OCT 27 (300), 1997
14:30:37.021
973001430CL2
BE2D 310
OCT 27 (300), 1997
14:30:37.021
973001430CL3
BE2D 040
OCT 27 (300), 1997
14:30:37.021
BE2U zzz
OCT 27 (300), 1997
14:30:37.021
BE2U 310
OCT 27 (300), 1997
14:30:37.021
BE2U 040
OCT 27 (300), 1997
14:30:37.021
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

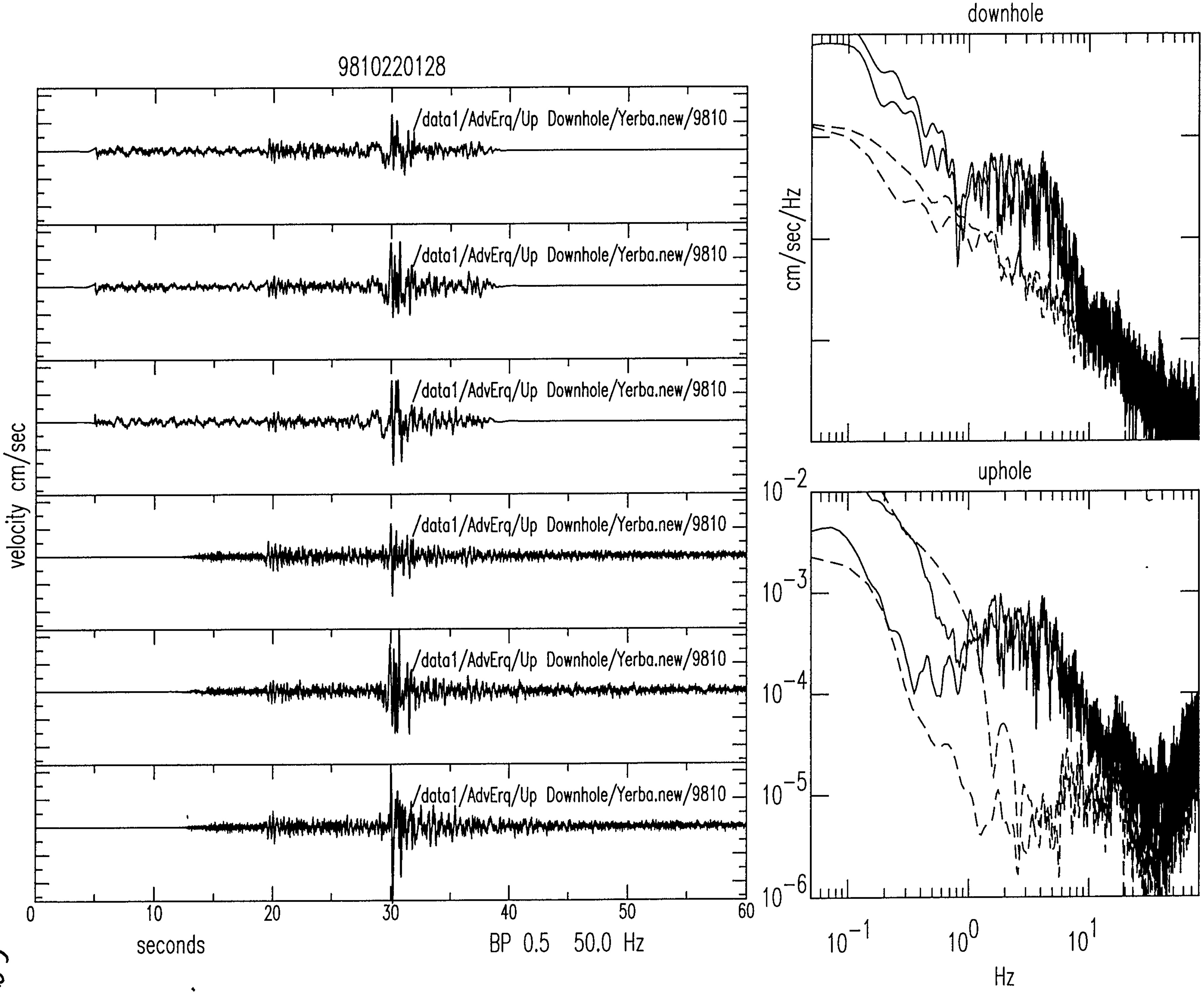

9711192105
973232104CL1
BE2D zzz
NOV 19 (323), 1997
21:05:10.391
973232104CL2
BE2D 310
NOV 19 (323), 1997
21:05:10.391
973232104CL3
BE2D 040
NOV 19 (323), 1997
21:05:10.391
BE2U zzz
NOV 19 (323), 1997
21:05:10.391
BE2U 310
NOV 19 (323), 1997
21:05:10.391
BE2U 040
NOV 19 (323), 1997
21:05:10.391
velocity cm/sec
0.005
0.000
−0.005
−0.010
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
cm/sec/Hz
seconds
uphole
BP 0.5 50.0 Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz



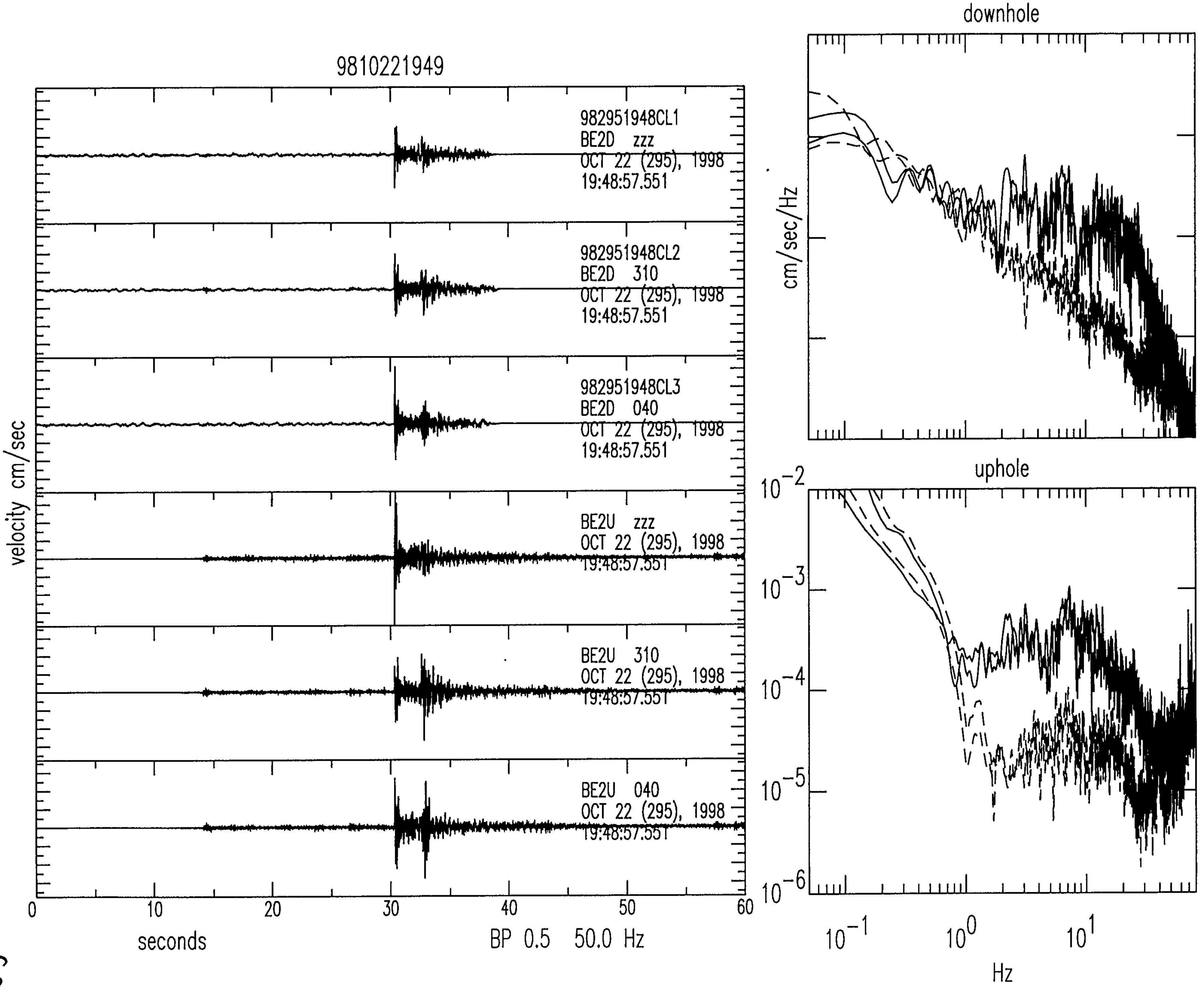
9801171000 – uphole
980170959CL1
BE2D zzz
JAN 17 (017), 1998
09:59:58.318
980170959CL2
BE2D 310
JAN 17 (017), 1998
09:59:58.318
980170959CL3
BE2D 040
JAN 17 (017), 1998
09:59:58.318
BE2U zzz
JAN 17 (017), 1998
BE2U 310
JAN 17 (017), 1998
BE2U 040
JAN 17 (017), 1998
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz



9810201246
982931245CL1
BE2D zzz
OCT 20 (293), 1998
12:46:03.431
982931245CL2
BE2D 310
OCT 20 (293), 1998
12:46:03.431
982931245CL3
BE2D 040
OCT 20 (293), 1998
12:46:03.431
BE2U zzz
OCT 20 (293), 1998
12:46:03.431
BE2U 310
OCT 20 (293), 1998
12:46:03.431
BE2U 040
OCT 20 (293), 1998
12:46:03.431
X 10-3
velocity cm/sec
seconds
BP 0.5 50.0 Hz
cm/sec/Hz
uphole
Hz

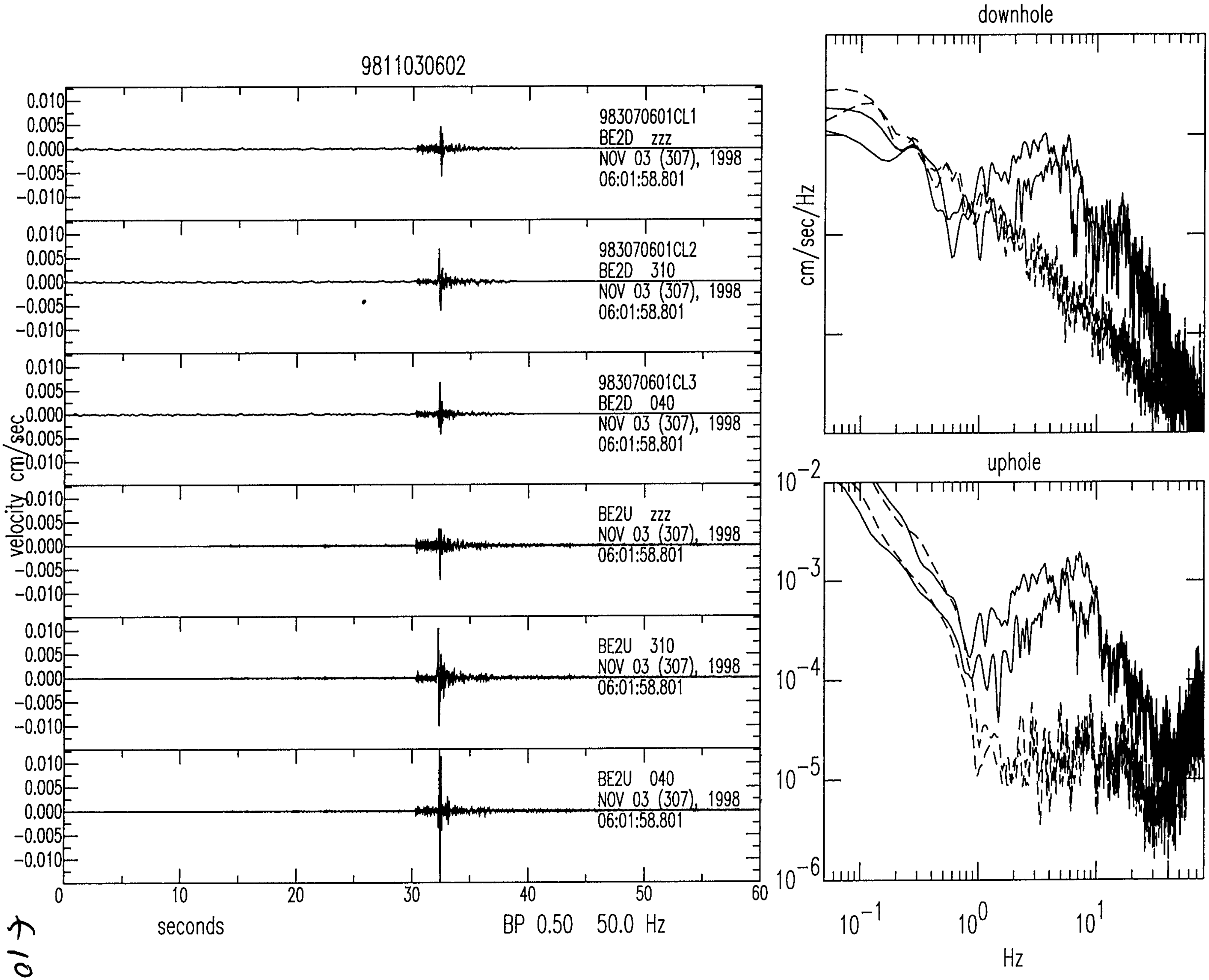

9810220128
/data1/AdvErq/Up Downhole/Yerba.new/9810
/data1/AdvErq/Up Downhole/Yerba.new/9810
/data1/AdvErq/Up Downhole/Yerba.new/9810
/data1/AdvErq/Up Downhole/Yerba.new/9810
/data1/AdvErq/Up Downhole/Yerba.new/9810
/data1/AdvErq/Up Downhole/Yerba.new/9810
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

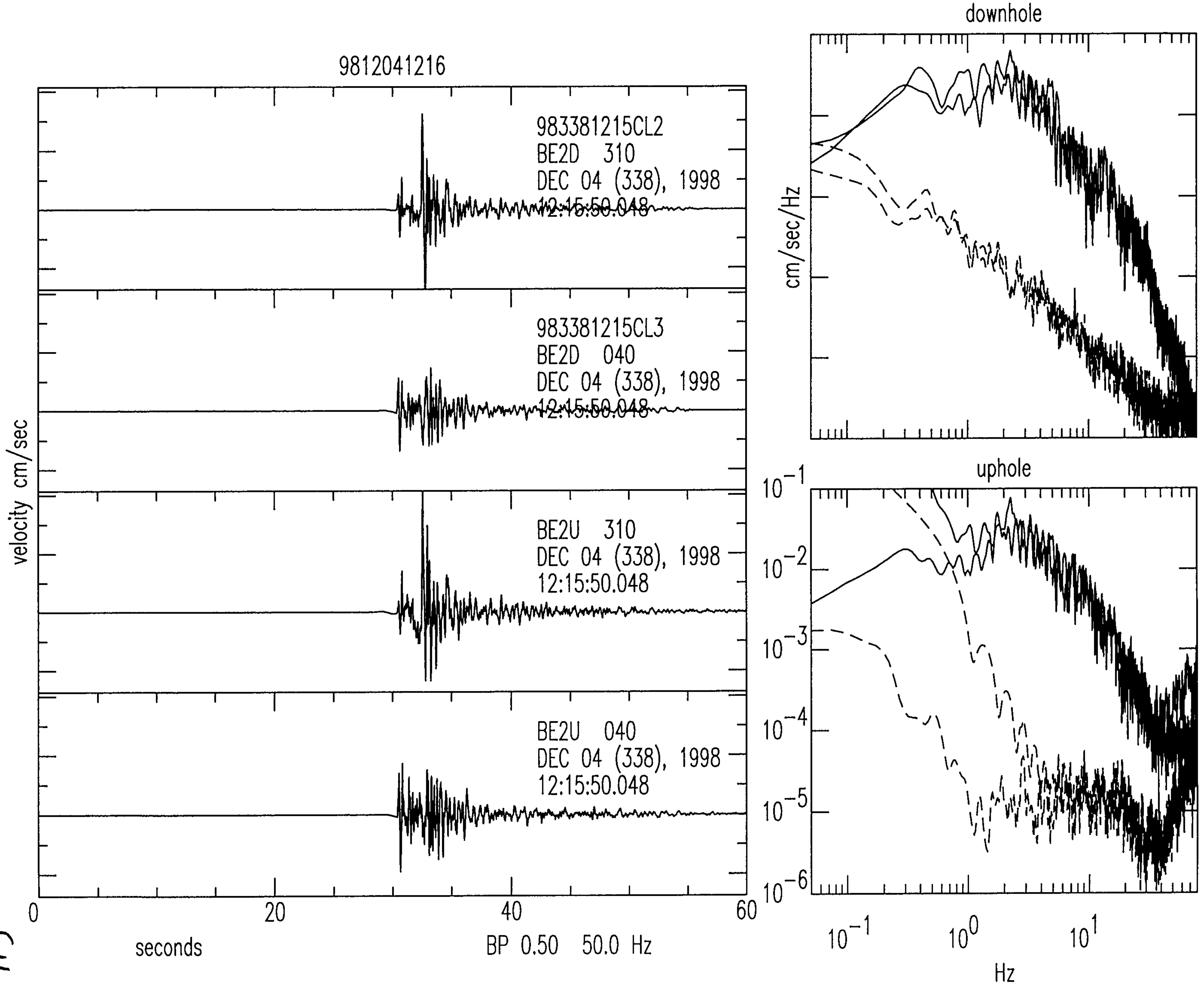
83



9810221949
982951948CL1
BE2D zzz
OCT 22 (295), 1998
19:48:57.551
982951948CL2
BE2D 310
OCT 22 (295), 1998
19:48:57.551
982951948CL3
BE2D 040
OCT 22 (295), 1998
19:48:57.551
BE2U zzz
OCT 22 (295), 1998
19:48:57.551
BE2U 310
OCT 22 (295), 1998
19:48:57.551
BE2U 040
OCT 22 (295), 1998
19:48:57.551
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

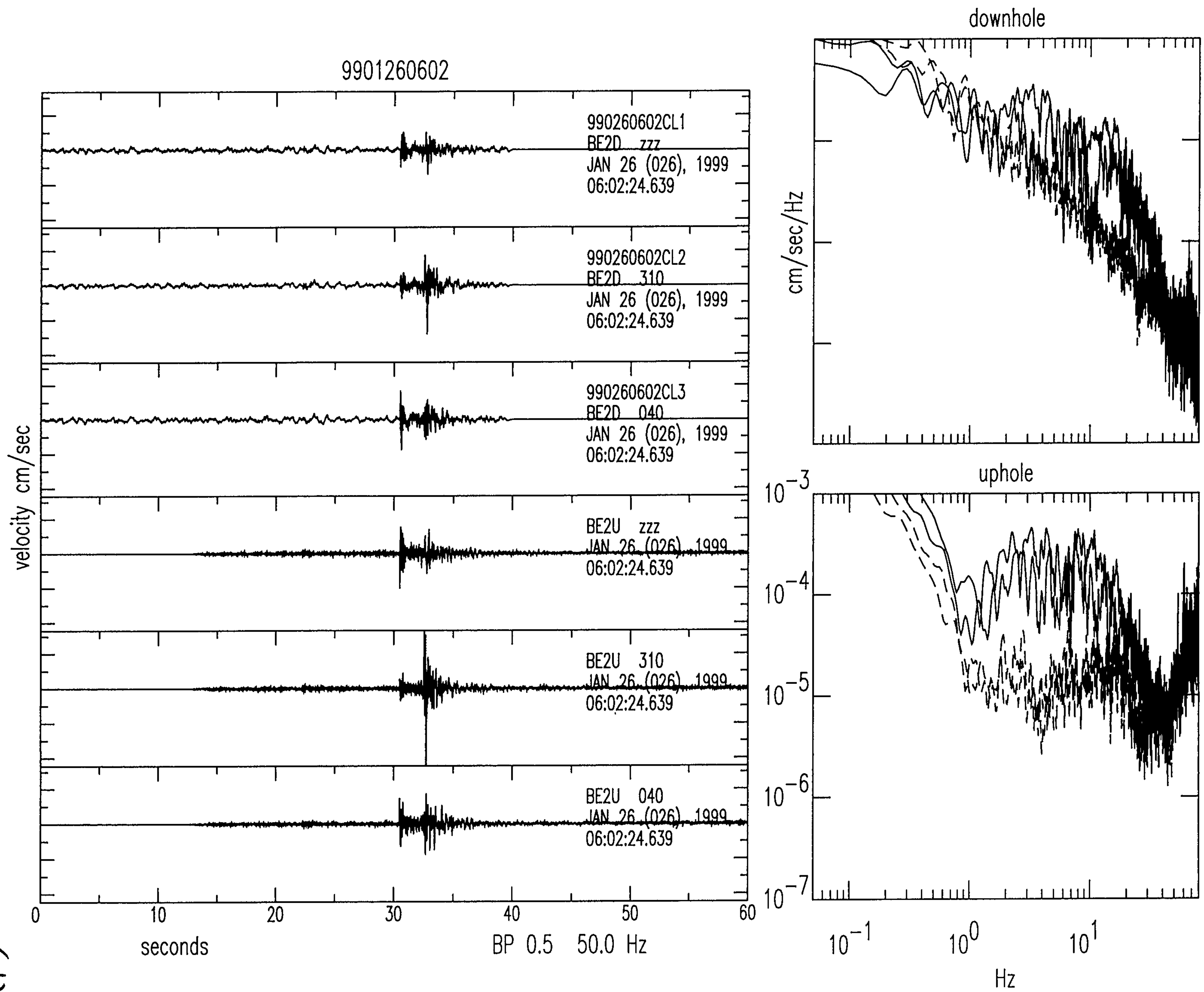

49


9811030602
983070601CL1
BE2D zzz
NOV 03 (307), 1998
06:01:58.801
983070601CL2
BE2D 310
NOV 03 (307), 1998
06:01:58.801
983070601CL3
BE2D 040
NOV 03 (307), 1998
06:01:58.801
BE2U zzz
NOV 03 (307), 1998
06:01:58.801
BE2U 310
NOV 03 (307), 1998
06:01:58.801
BE2U 040
NOV 03 (307), 1998
06:01:58.801
velocity cm/sec
seconds
BP 0.50 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz

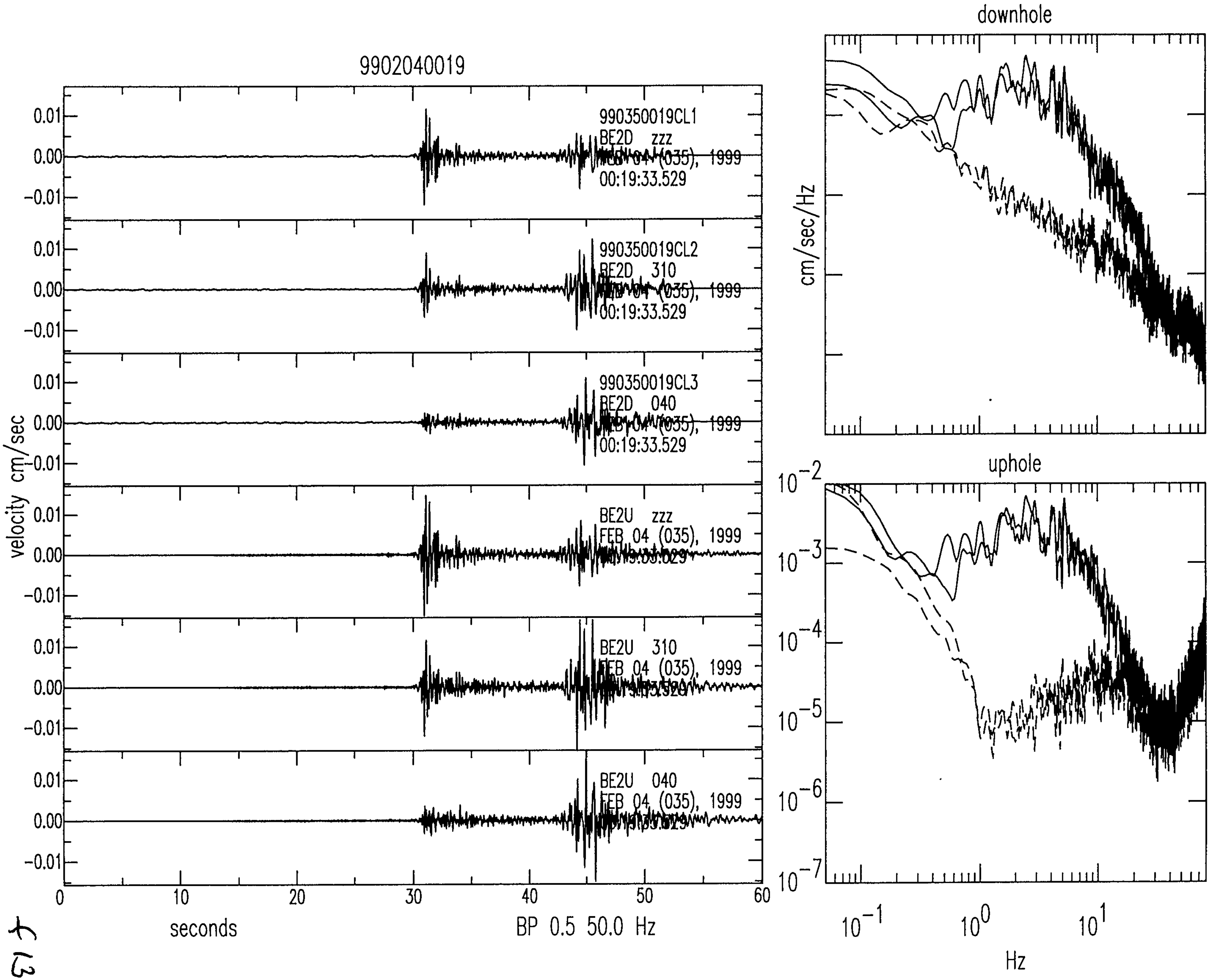


9812041216
983381215CL2
BE2D 310
DEC 04 (338), 1998
12:15:50.048
983381215CL3
BE2D 040
DEC 04 (338), 1998
12:15:50.048
BE2U 310
DEC 04 (338), 1998
12:15:50.048
BE2U 040
DEC 04 (338), 1998
12:15:50.048
velocity cm/sec
0
20
40
60
seconds
BP 0.50 50.0 Hz
downhole
uphole
cm/sec/Hz
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-1
10^0
10^1
Hz

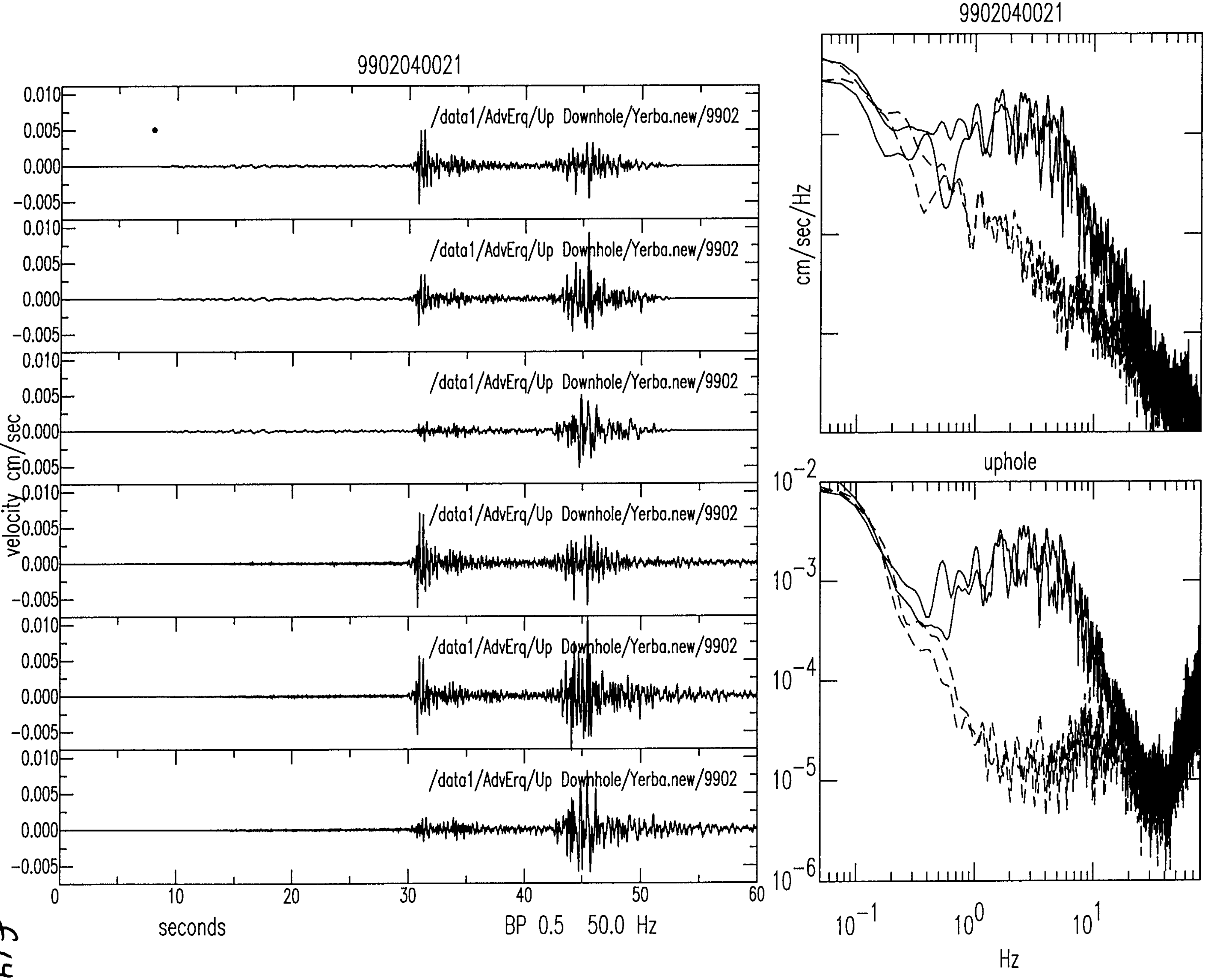

117



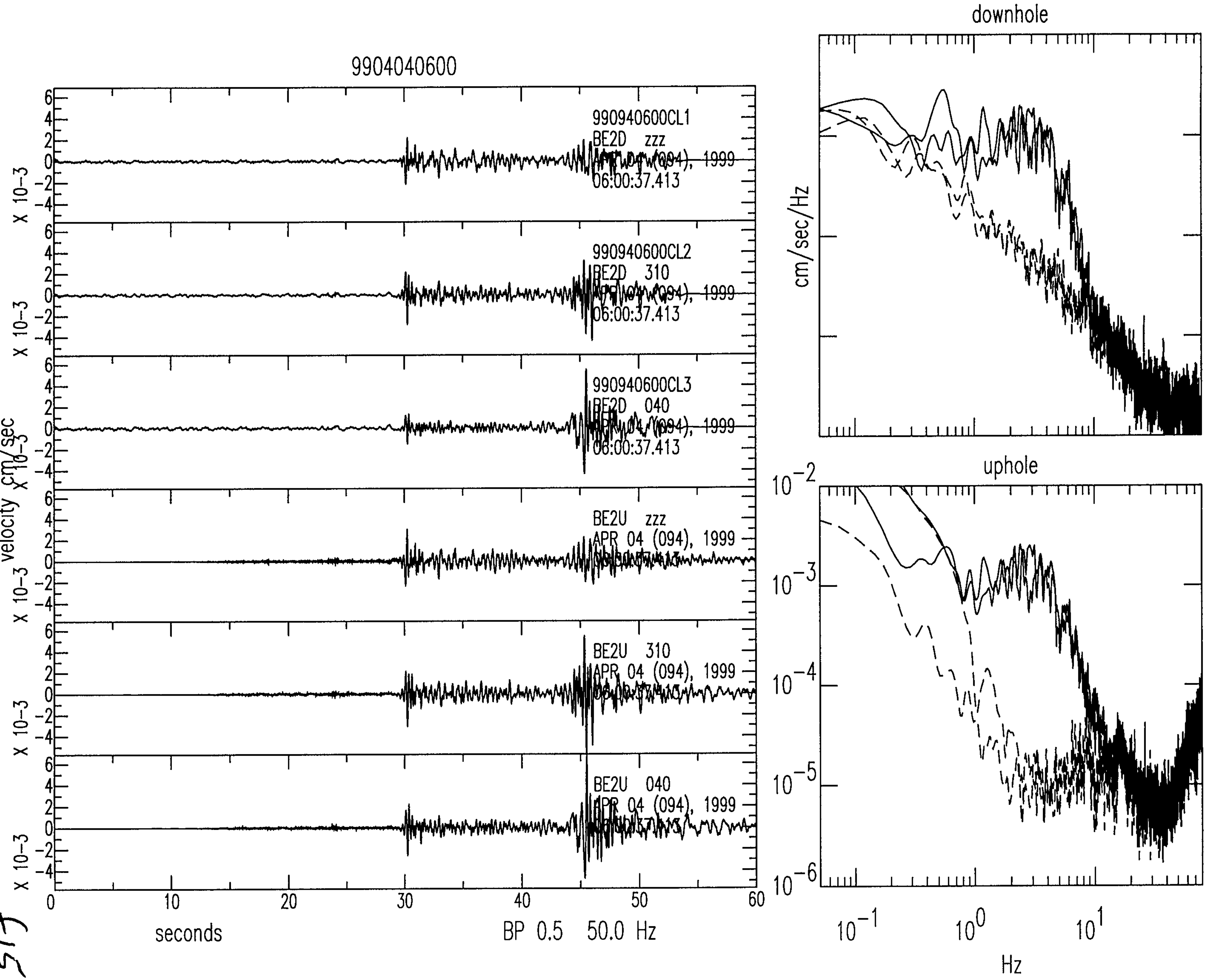
9901260602
990260602CL1
BE2D zzz
JAN 26 (026), 1999
06:02:24.639
990260602CL2
BE2D 310
JAN 26 (026), 1999
06:02:24.639
990260602CL3
BE2D 040
JAN 26 (026), 1999
06:02:24.639
BE2U zzz
JAN 26 (026), 1999
06:02:24.639
BE2U 310
JAN 26 (026), 1999
06:02:24.639
BE2U 040
JAN 26 (026), 1999
06:02:24.639
velocity cm/sec
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
10^-3
10^-4
10^-5
10^-6
10^-7
10^-1
10^0
10^1
Hz


9902040019
990350019CL1
BE2D zzz
FEB 04 (035), 1999
00:19:33.529
990350019CL2
BE2D 310
FEB 04 (035), 1999
00:19:33.529
990350019CL3
BE2D 040
FEB 04 (035), 1999
00:19:33.529
BE2U zzz
FEB 04 (035), 1999
BE2U 310
FEB 04 (035), 1999
BE2U 040
FEB 04 (035), 1999
velocity cm/sec
0.01
0.00
-0.01
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

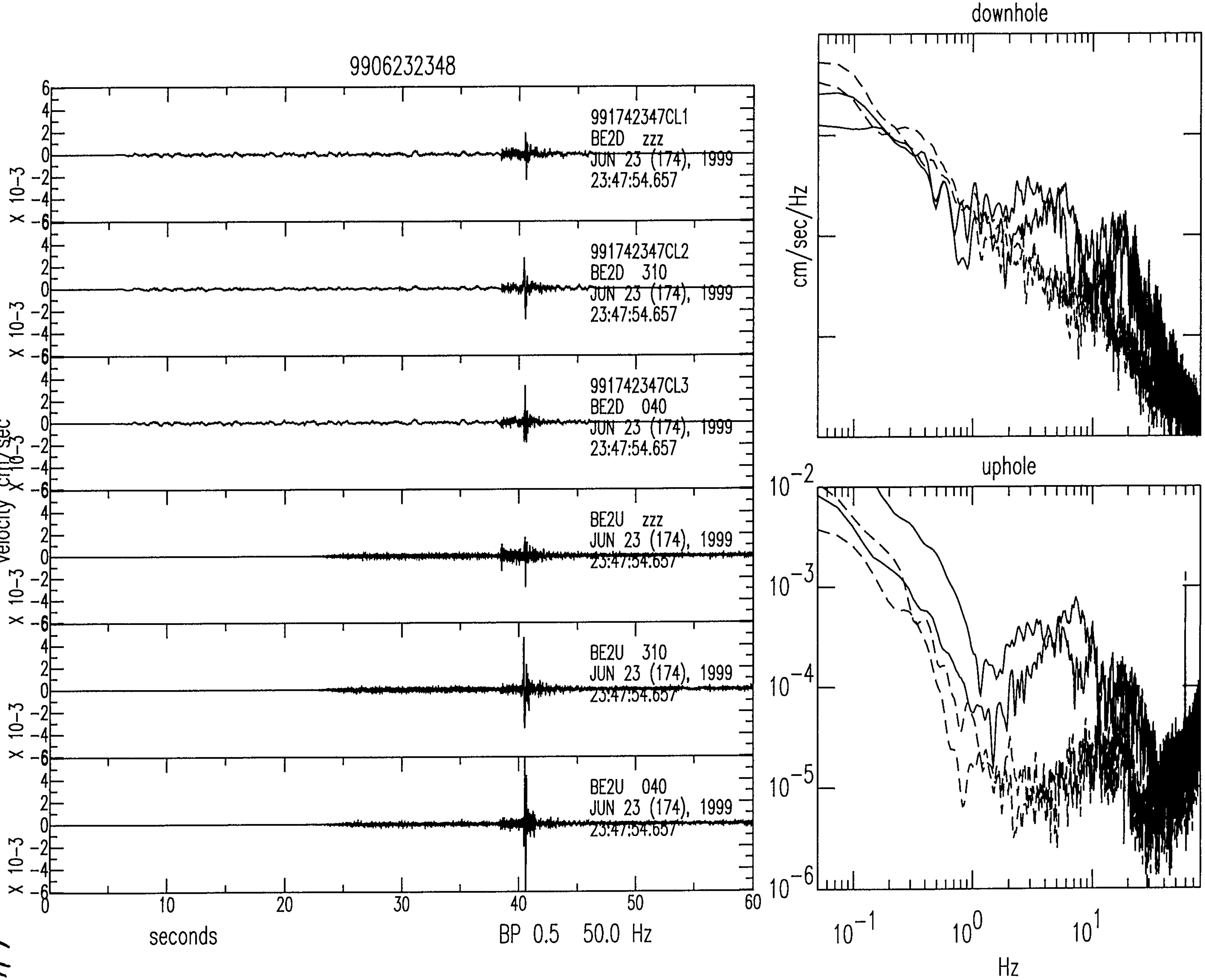
f 13



9902040021
/data1/AdvErq/Up Downhole/Yerba.new/9902
velocity cm/sec
0.010
0.005
0.000
−0.005
0
10
20
30
40
50
60
seconds
BP 0.5 50.0 Hz
9902040021
cm/sec/Hz
uphole
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-1}$
$10^{0}$
$10^{1}$
Hz

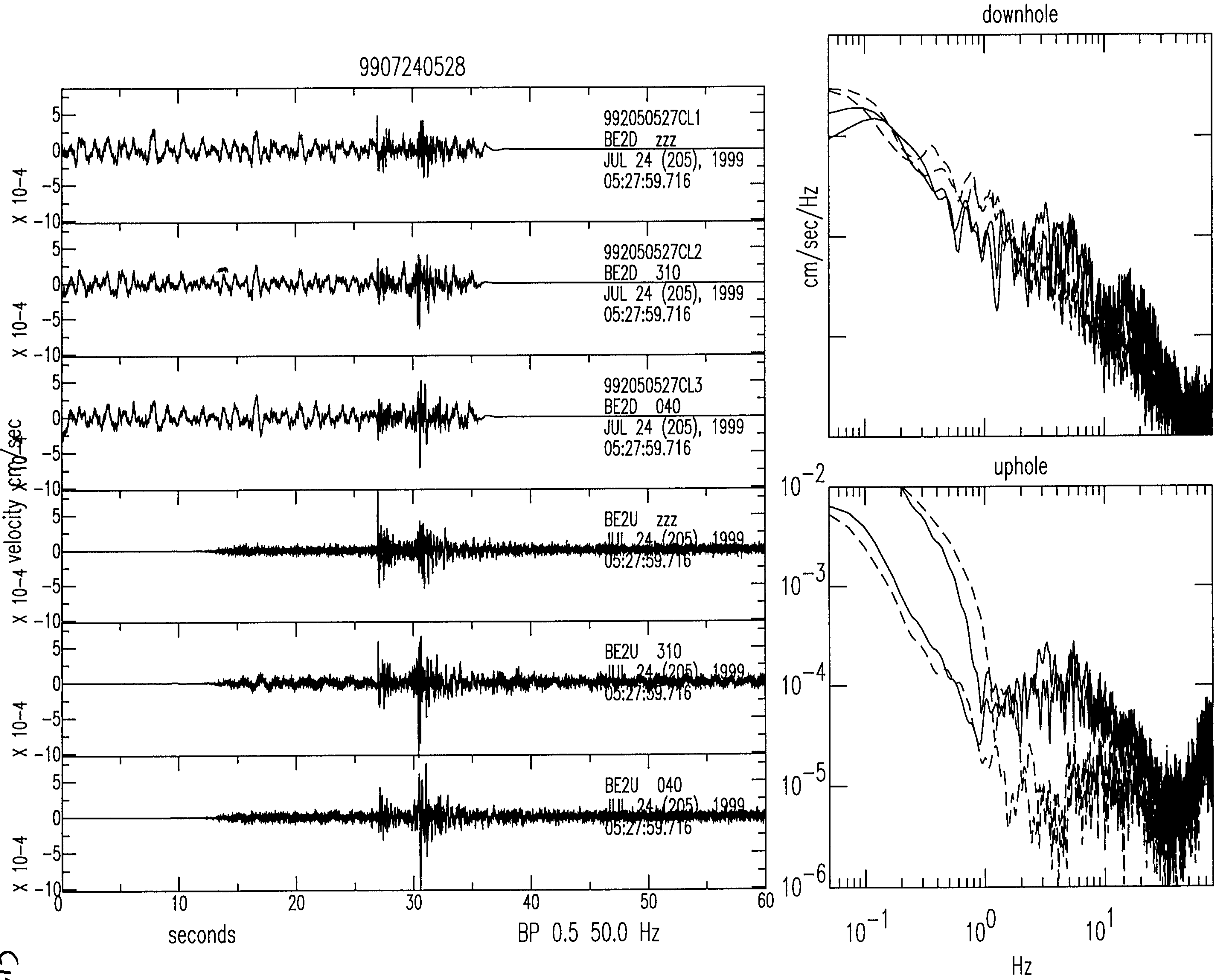


9904040600
990940600CL1
BE2D zzz
06:00:37.413
990940600CL2
BE2D 310
06:00:37.413
990940600CL3
BE2D 040
06:00:37.413
BE2U zzz
APR 04 (094), 1999
BE2U 310
APR 04 (094), 1999
BE2U 040
APR 04 (094), 1999
velocity cm/sec
X 10−3
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz

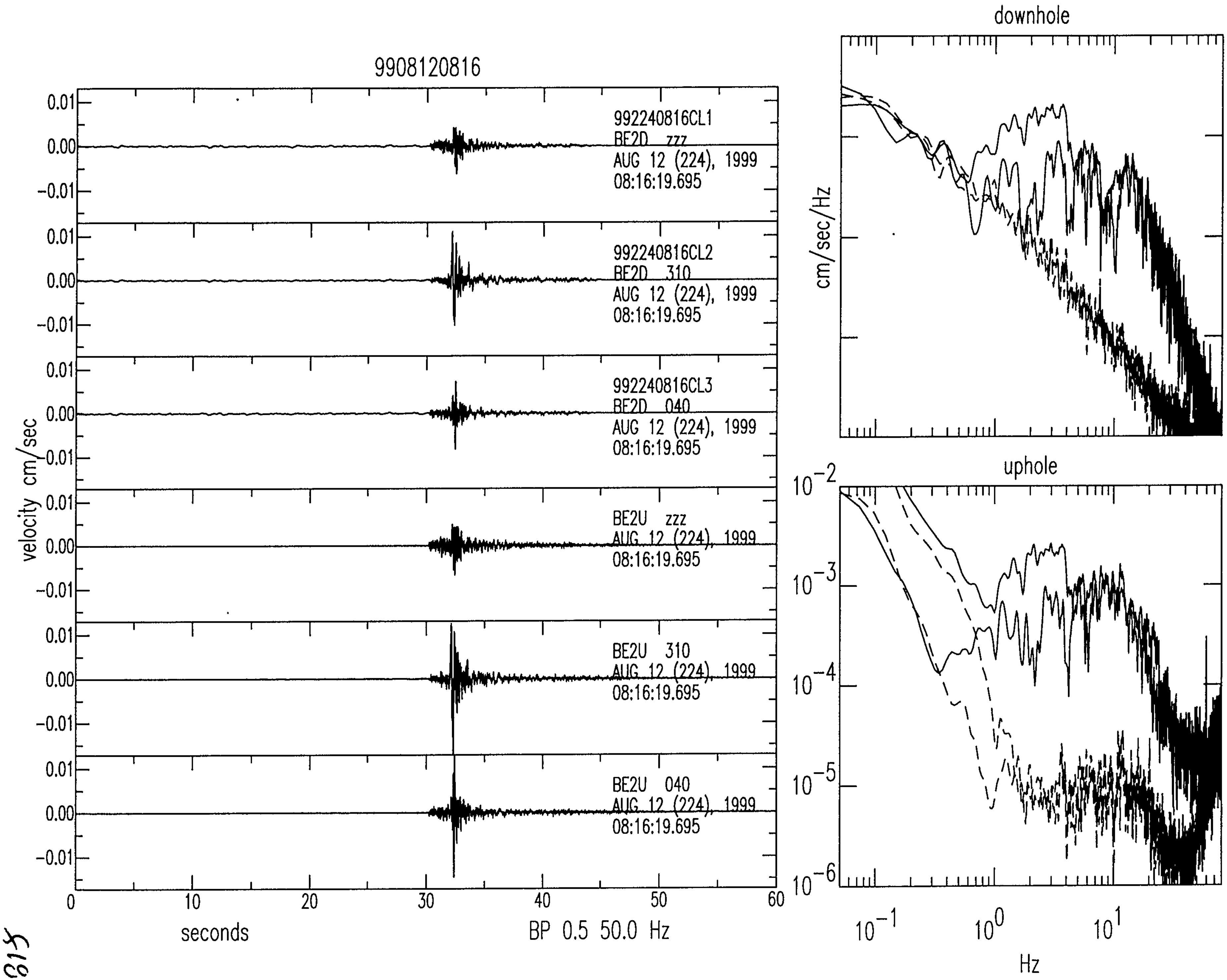


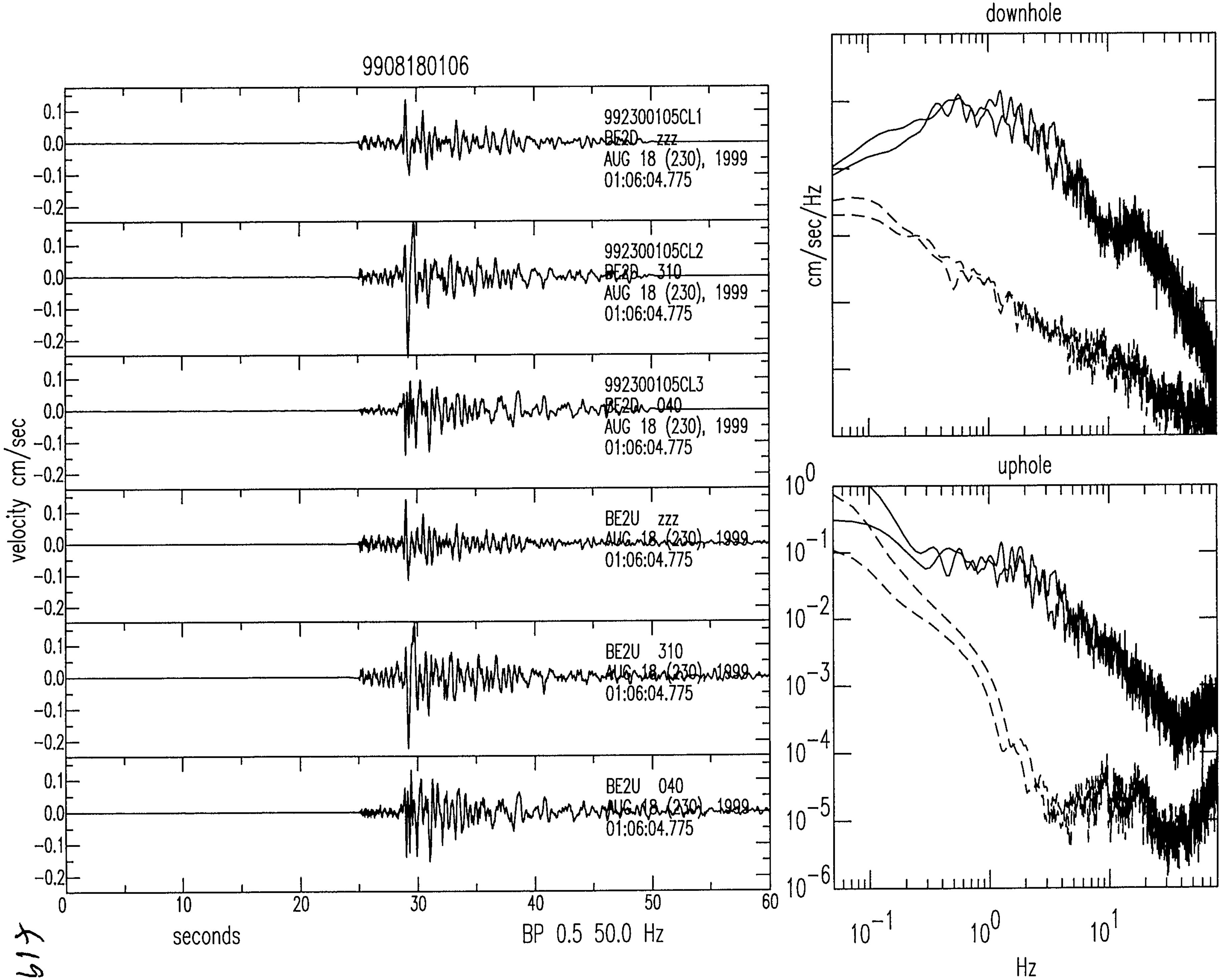
9906232348
991742347CL1
BE2D zzz
JUN 23 (174), 1999
23:47:54.657
991742347CL2
BE2D 310
JUN 23 (174), 1999
23:47:54.657
991742347CL3
BE2D 040
JUN 23 (174), 1999
23:47:54.657
BE2U zzz
JUN 23 (174), 1999
23:47:54.657
BE2U 310
JUN 23 (174), 1999
23:47:54.657
BE2U 040
JUN 23 (174), 1999
23:47:54.657
X 10-3
velocity cm/sec
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz


91f

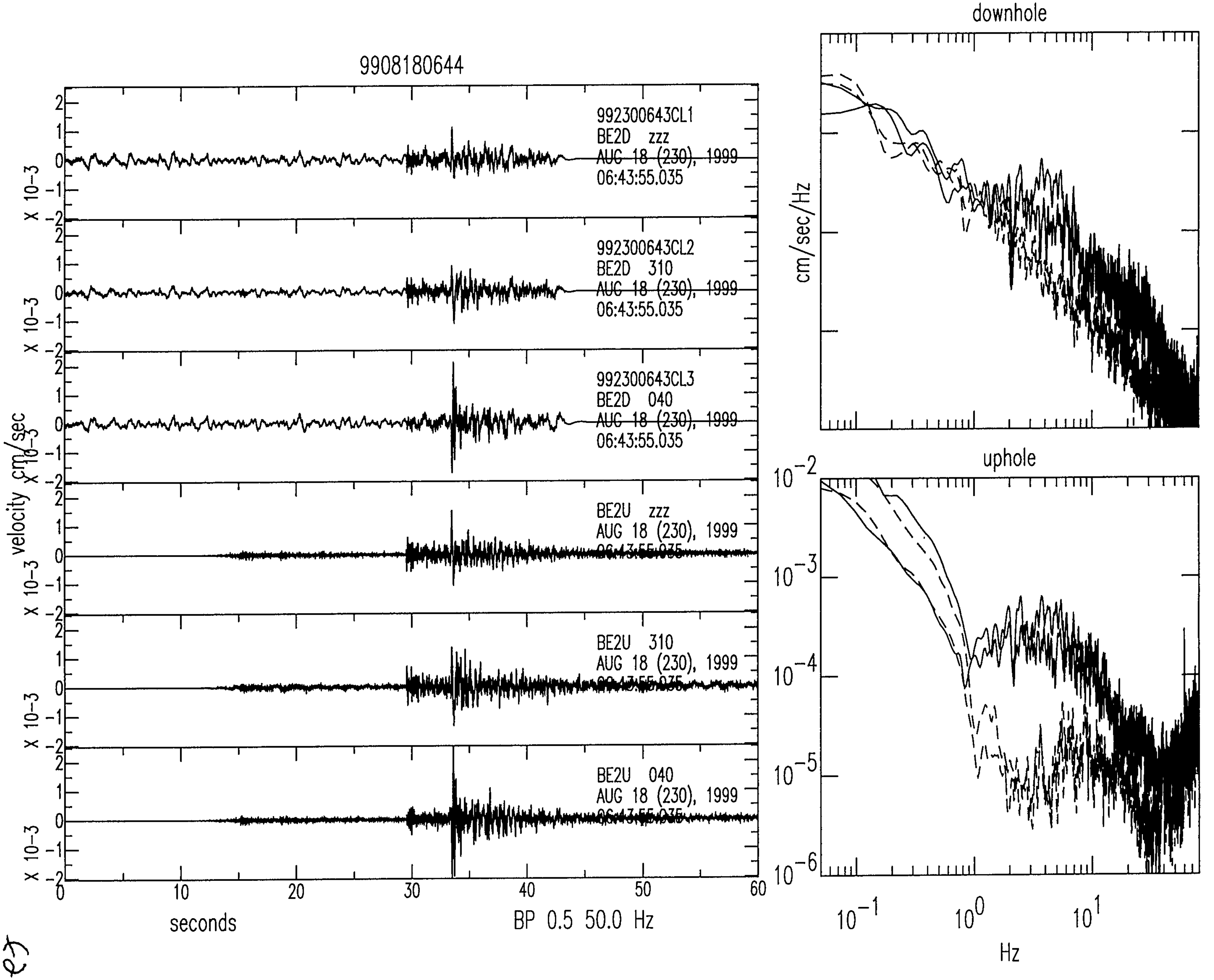

9907240528
992050527CL1
BE2D zzz
JUL 24 (205), 1999
05:27:59.716
992050527CL2
BE2D 310
JUL 24 (205), 1999
05:27:59.716
992050527CL3
BE2D 040
JUL 24 (205), 1999
05:27:59.716
BE2U zzz
JUL 24 (205), 1999
05:27:59.716
BE2U 310
JUL 24 (205), 1999
05:27:59.716
BE2U 040
JUL 24 (205), 1999
05:27:59.716
velocity cm/sec
X 10-4
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz

417


9908120816
992240816CL1
BE2D zzz
AUG 12 (224), 1999
08:16:19.695
992240816CL2
BE2D 310
AUG 12 (224), 1999
08:16:19.695
992240816CL3
BE2D 040
AUG 12 (224), 1999
08:16:19.695
BE2U zzz
AUG 12 (224), 1999
08:16:19.695
BE2U 310
AUG 12 (224), 1999
08:16:19.695
BE2U 040
AUG 12 (224), 1999
08:16:19.695
velocity cm/sec
0.01
0.00
-0.01
0 10 20 30 40 50 60
seconds
BP 0.5 50.0 Hz
downhole
cm/sec/Hz
uphole
10^-2
10^-3
10^-4
10^-5
10^-6
10^-1 10^0 10^1
Hz



9908180106
992300105CL1
BE2D zzz
AUG 18 (230), 1999
01:06:04.775
992300105CL2
BE2D 310
AUG 18 (230), 1999
01:06:04.775
992300105CL3
BE2D 040
AUG 18 (230), 1999
01:06:04.775
BE2U zzz
AUG 18 (230), 1999
01:06:04.775
BE2U 310
AUG 18 (230), 1999
01:06:04.775
BE2U 040
AUG 18 (230), 1999
01:06:04.775
velocity cm/sec
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz


9908180644
992300643CL1
BE2D zzz
AUG 18 (230), 1999
06:43:55.035
992300643CL2
BE2D 310
AUG 18 (230), 1999
06:43:55.035
992300643CL3
BE2D 040
AUG 18 (230), 1999
06:43:55.035
BE2U zzz
AUG 18 (230), 1999
BE2U 310
AUG 18 (230), 1999
BE2U 040
AUG 18 (230), 1999
velocity cm/sec
X 10-3
seconds
BP 0.5 50.0 Hz
downhole
uphole
cm/sec/Hz
Hz